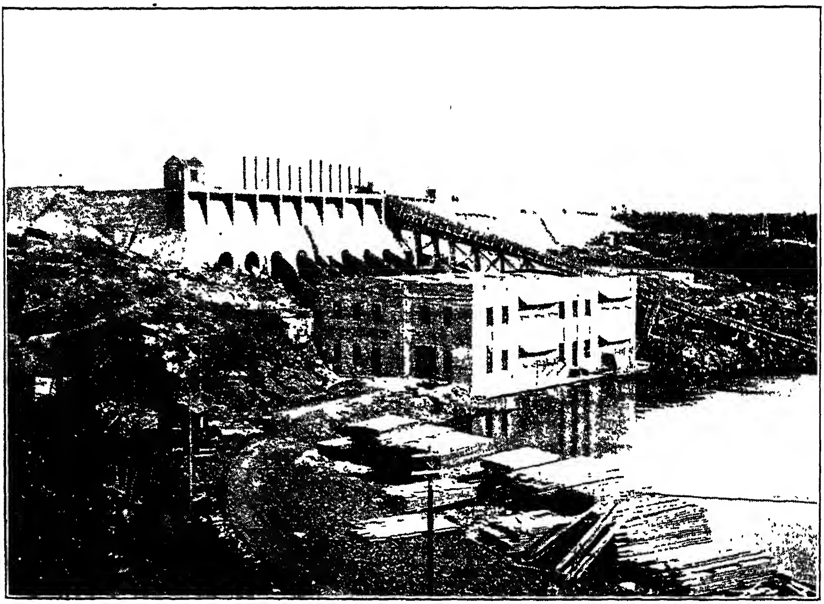
High Falls on the Peshtigo River, Wisconsin, before Development.
(E. C. Wild.)



The Hydro-Electric Development at High Falls. Building Located at Foot of Former Fall. Power Transmitted to Green Bay, Wisconsin, a Distance of about Sixty-two Miles.

HYDROLOGY

THE FUNDAMENTAL BASIS OF HYDRAULIC ENGINEERING

BY

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PREFACE

In the following pages the author has discussed some of the most important facts and principles of hydrology. The author believes, from his observations during more than 35 years of professional practice, that more failures have resulted in various hydraulic engineering projects from lack of adequate conceptions, on the part of the designing engineers, of the fundamental principles of hydrology and of the importance of hydrological factors than from defects in structural design. In many cases the engineer has based his work on unwarranted assumptions and has not possessed sufficient knowledge even to appreciate the necessity of hydrological investigations.

As a result of the lack of appreciation of the importance of the fundamental basis on which every sound hydraulic project must rest, numerous irrigation projects, water power plants and public water works have proved partial or complete failures for lack of adequate water supplies, life and property have been destroyed by failures of dams, inadequate reservoir spillways and protecting works, and drainage and flood protection enterprises have been undertaken with no adequate knowledge of necessary flood capacities. In many ways unnecessary losses are frequently entailed which have been largely due to the fact that the importance of hydrological information has not been sufficiently impressed upon the minds of hydraulic engineers.

The author has made no attempt in the following pages to furnish categorical answers to complex hydrological questions but has endeavored to show that the answers to the same questions may be and sometimes are reversed under different local conditions, and are always greatly modified thereby. He has found it necessary in almost every chapter to warn the engineer against attempts to solve hydrological problems by formulas or rules of thumb of restricted application and to insist in every case upon the necessity of conclusions based upon the detailed consideration of all the local factors in each problem.

While the author has emphasized the impossibility of a high degree of accuracy in the solution of most hydrological problems, he has also attempted to show that such problems are susceptible of a solution fully as accurate as in the case of most other engineering problems.

While hydrology is by no means a new subject it has received far less study and attention than its importance warrants. Some of the phenomena have been discussed in treatises on water supply and sewerage, but the subject has been introduced as a separate technical study in engineering schools only within the last fifteen years.

In 1904 the author issued his "Notes on Hydrology" as a basis for a course of study at the University of Wisconsin but it was found to be not wholly satisfactory and has long since been out of print. The present work is the result of notes derived from both investigation and practice and has been prepared primarily for the author's classes in the University of Wisconsin. Nothing is introduced which the author has not found to be of practical importance in his own professional work, and much has been omitted on account of the necessary limitations of this volume. The literature on the subject is very extensive, and a carefully selected list of the most important sources of information has been added to each chapter.

It is perhaps needless to call attention to the necessity of much further investigation and study in order to correlate correctly many of the intricate factors of hydrological problems and to make their true relations manifest. On the subject of stream flow, one of the most intricate of these problems, the various methods of correlation which have been suggested by various hydrologists are shown in order to explain both their strength and weakness, and in order to indicate the desirable direction of further investigations. The methods used and suggested by the author for the solution of stream flow problems are not offered as final methods but simply as the best practical methods which in his judgment have been devised up to the present time.

The author has endeavored to give credit to the source of all illustrations and methods in connection with their presentation. He acknowledges his indebtedness to the technical press and to various reports, technical works and society proceedings to which reference has been made. His acknowledgments are especially due to Mr. L. R. Balch for material assistance in the preparation of this volume, particularly in connection with the editorial work. Acknowledgments for valuable suggestions are also due to the author's associates, Messrs. C. V. Seastone and F. W. Scheidenhelm.

DANIEL W. MEAD

Madison, Wisconsin, September, 1919.

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HYDROLOGY

CHAPTER I

INTRODUCTION

1. **Hydrology.**—Hydrology treats of the laws of the occurrence and distribution of water over the earth's surface and within the geological strata, and of its sanitary, agricultural and commercial relations. Hydrology in its broadest extent treats of the properties, laws and phenomena of water, of its physical, chemical and physiological relations, of its distribution and circulation throughout the habitable earth, and of the effect of this circulation on human lives and interests. This circulation is one of the important influences on the growth and development, or the changes and evolution from past through present to future forms and conditions in the earth's history, and has a most important bearing on the geographic extent of human activities. This circulation of water above, on and within the earth's crust, is as important and necessary in geological change and development as is the circulation of blood in the animal body or the circulation of sap to vegetable life. The latter are also dependent on water, of which they are largely composed.

The phenomena and laws of all sciences are so interwoven that it has been said if a student has a complete knowledge of any one he will have a complete knowledge of all. In a practical way, this idea is true to the extent that no science can be satisfactorily acquired without trespassing to a degree on many other sciences. So in the study of Hydrology we must, to an extent at least, seek information from Meteorology, Geography, Geology, Physiography, Agriculture, Forestry, and from the field of Hydraulic Engineering of which Hydrology is the basic study.

Hydrology discusses Hydro-Meteorology principally in relation to the occurrence, distribution, variation and disposal of rainfall and the runoff resulting therefrom in drought and in flood. It discusses the modifications of the runoff caused by evaporation, topography, geology, temperature, and various other factors, and the variations in runoff as these factors vary in importance with the location or with the season. The great variations in the unit runoff under similar rainfall conditions but

different physical conditions, and under similar physical conditions but different rainfall conditions, are investigated, and the marked differences which arise in different parts of the country with these differences in conditions are discussed. The effects of storage, of cultivation, of forestation and of other artificial physical modifications of the drainage area on the flow of streams, are also considered.

Hydrology discusses Hydrography and Physiography in relation to the distribution and circulation of water over the earth's surface and the physical features that modify and influence such distribution and circution. It discusses Hydro-Geology or the occurrence of water in the strata, and the laws of its occurrence and flow. This must presuppose or include a sufficient study of general Geology to give a comprehensive knowledge of the geological limitations which must be expected in hydrographic conditions and of the modifications due to geological changes. Water as a geological agent is discussed, and through such study a comprehension of the birth, growth, and the development of drainage systems and of rivers is attained.

2. Prevalence of Law in all Natural Phenomena.—The study of Hydrology demonstrates the prevalence of law in the occurrence of all natural phenomena.

Rainfall and its accompanying phenomena are proverbially inconsistent, but Hydrology shows that there are limitations to such inconsistencies and that those limitations are quite as narrow and exact as those that must be considered in other engineering calculations which must be cared for by the "factor of safety" which is simply a "factor of inconsistency" in the qualities or occurrences of conditions with which the engineer always has to deal.

The study of the development of rivers demonstrates that the apparently lawless and erratic action of streams follows laws more or less distinct, which must be studied and comprehended before intelligent river conservancy becomes possible.

The laws which control the circulation of water, on which its presence or absence depend, and which modify and define its occurrence, attract attention and become of practical importance only as comprehension of them permits of such adaptation to human affairs as will reduce or eliminate the injurious results which may otherwise happen during the occurring cycle, or will modify or effect a controlling influence which will adapt the occurrence to useful ends.

3. Hydrological Influence on Early Settlement.—In primitive settlements, a profound knowledge of the detail of these laws and con-

ditions was of small importance. Normal conditions might render a locality unsuited to human use. The land might be too dry or too wet for agriculture and it would not be utilized. It might be subject to overflow from the tides or the river floods and remain unsettled, or if an attempt was made to utilize or to settle, it was abandoned on account of the rare occurrence of overflow, with more or less resulting loss when such overflow occurred. As land was abundant and of but little value, the individual had but to choose the location where the conditions were best suited to his purpose.

The first settlements of a new country have normally and permanently occurred where water for drinking and other domestic uses was readily obtained; where the normal rainfall, both in quantity and distribution, was adequate for agriculture; where the land was free from both drought and overflow; where intercommunication among settlements was readily accomplished; where the location was accessible to navigation; and where water power could be cheaply and readily developed for primitive manufacturing. All of these elements have had an important influence in the development of every country. The earlier civilization developed along those seas, lakes and rivers where navigation was possible and where other elements were favorable to settlement. As the art of navigation developed so that the ocean could be crossed, the early settlements in new lands were along the shore where good harbors were found and where safe and ready ingress and egress were assured.

Exploration and settlements followed the lines of navigation, and in America, the St. Lawrence River, the Great Lakes, and the Mississippi and Ohio Rivers afforded the lines of least resistance to the explorer and the settler. The settlement of New York spread up the Hudson and along the tributary rivers because of accessibility together with other favorable conditions, and the Delaware and James Rivers and Chesapeake Bay had a similar influence on the settlement of Pennsylvania, Maryland and Virginia.

As other methods of transportation have developed, interior towns remote from navigable waterways have resulted, but the larger commercial communities are still situated where navigation as well as other means for transportation is available.

4. Effect of Development on Importance of the Subject.—With the growth and development of the country, other hydrological factors exerted their influence. The water powers of Lowell and Holyoke were the prime cause of early industrial development at these places.

The same influences prevailed at numerous other locations in the East.

The growth and concentration of population soon affect land values, and lands at first unutilized, on account of unfavorable hydrological conditions, gradually attract attention on account of their favorable location, and the questions of their reclamation, protection and utilization become of increasing consequence. A knowledge of the conditions that influence such lands gradually became important. The limits and extent of the unfavorable conditions were examined and considered; primitive attempts were made at their reclamation, often with destructive results because the extreme conditions were unknown or unrecognized. Mankind gradually determined, by dearly acquired experience, the necessary extent and limits of its powers. In some cases limiting values required only small effort; in others the values were so great that extensive efforts and expense were warranted.

In early reclamation work only crude efforts were possible for no knowledge or precedent existed, but as the development proceeded, the principles underlying successful work were made manifest, the influences of conditions were determined, and the results of similar efforts were more readily and certainly assured.

5. Basis of Present Engineering Practice.—Modern engineering endeavor is a development from the successful primitive efforts of the pioneer to better his condition, to make his home and property safe and accessible, and to secure and surround himself with the conveniences of civilization. From the experience of man in all climes and in all countries, have been established the principles on which the success of all engineering work depends. There is little essentially new or novel that is safe. The adoption or extension of past experience to new circumstances and conditions is the sound basis of successful work. Research along new and original lines is but moderately productive and is seldom warranted in the solution of practical problems; that is the function of the pioneer and the laboratory. The engineer with the great practical problem must call to his assistance the successful experience of the past, and must build along lines that do not admit the possibility of failure. It becomes therefore of fundamental importance for the engineer first to recognize his problem, and all of the conditions and principles on which its solution depends, for the correct solution can depend on nothing less.

6. Extent of Knowledge necessary for Successful Engineering Work.—In the application of any science to practical ends, it must be remembered that for real substantial success a knowledge of many

sciences and many facts is essential. Hydrologically, a water supply for any purpose may be satisfactory but it must be conserved and developed by correct engineering design and construction to be an engineering success. Successful adaptation of sound engineering and construction may bring about satisfactory constructive results but still other things are needed for ultimate success. The legal aspect demands attention, the laws of the land must be observed, and the legal rights must be properly secured, but even more is needed. Business and financial conditions must also be considered. Can the proposition be made a commercial success? Will the use to which the project is to be put warrant the necessary financial outlay and produce a sufficient income to guarantee satisfactory results for the investment necessary for sound engineering work, under the laws of the land, and develop the hydrological resources to the extent required?

For real success, each aspect is both independent and related to all others; failure in one is failure in all. No one is the most important unless unrecognized, when its importance at once predominates. At least a limited understanding of hydrological principles is prerequisite to the successful solution of the simplest problems in hydraulic engineering. For the purpose of investigating the more complicated problems, a more detailed knowledge of this science is essential, and the more extended the knowledge of this subject, the greater the assurance of the successful solution of all such problems.

7. **Casualties Due to Lack of Hydrological Knowledge.**—Failures more or less serious have resulted in every branch of hydraulic engineering from the neglect to investigate the fundamental hydrological conditions and to appreciate the importance of fundamental hydrological knowledge.

Water power installations have been built without sufficient knowledge of the régime of the stream on which their success depends, resulting in failures of greater or less consequence. In many cases the deficient supply has resulted in financial failure, the plant being perhaps continued in operation after liquidation by the original investors. In some cases even more marked failures have resulted. A water power plant, taking its supply from a mountain lake, was constructed a few years ago in Virginia. The lake was drained by the plant soon after operation began, and the dependable supply was found to be so small that the plant was abandoned. A dam and power plant were constructed within the decade on a Wisconsin river which proved to have a normal flow so deficient in quantity that the dam was abandoned and the

machinery moved to another location on a larger and more dependable stream.

To the lack of proper geological knowledge and investigation must be attributed many expensive and serious failures. The failure of the dam at Austin, Texas,[1] was due to faulty foundation construction in the poor quality, open textured and faulted limestone. Similar conditions coupled with poor construction propably gave rise to the disastrous failure of the dam at Austin, Pennsylvania, in 1911,[2] and of the Stoney River Dam in West Virginia.[3]

Cities have been founded in needlessly exposed positions and left unprotected, or so poorly protected as to be subject to great financial damage and loss of life from floods. Extensive damages have also been caused to farm and agricultural communities from similar causes. The Passaic flood of 1903[4] resulted from an unusually large rainfall and from rapidly melting snow. From October 8th to 11th, 11.74 inches of rain fell in the Passaic River basin. All storage on the basin was filled at the beginning of the storm, and in the resulting flood bridges were washed out, a large number of dams failed, many highways were destroyed, and much damage occurred to manufacturing plants and real estate.

In the Kansas City flood[5] of the same year, a rainfall of five to ten inches occurred in sixteen days on the drainage area of the Kansas River, at a time when the river was above its normal flow and with the ground saturated. At Lecompton, the gage was twelve inches higher than any readings in twenty-two years. At Kansas City, the flood was fourteen feet above the danger line and two feet above the highest point reached by the previously highest recorded flood of June 20, 1844. The damage that resulted was very great.

The Johnstown flood,[6] which occurred in 1889, was probably one of the greatest disasters of the kind on record. This disaster was due to the insufficient provision of spillway. Continued rains saturated the soil and caused practically all of the water of a succeeding heavy storm

[1] Water Supply Paper No. 40, by T. U. Taylor. Eng. News, September 5, 1901; Eng. News, April 12, 1900.

[2] Dam Failure at Austin, Pa. Eng. News, March 17, 1910.

[3] Break in Stoney River Dam. Eng. News, January 22, 1914.

[4] Passaic River Flood of 1903. New Jersey. U. S. G. S. Water Supply & Irrigation Paper No. 92, M. O. Leighton.

[5] Kansas City Flood of 1903. Destructive Floods of 1903, by E. C. Murphy. U. S. G. S. Water Supply and Irrigation Paper No. 96.

[6] Johnstown, Pennsylvania, Flood of 1889. Eng. News, June 1, 8, 15 and 22; July 13, and August 17, 1889.

to run off rapidly, raising the water in the reservoir and finally overtopping and destroying the earth fill dam, and releasing a great flood of water which descended on the unprotected cities and villages below with great loss of property and life. Over five thousand lives were lost in this flood, and the property damage amounted to many millions.

The insufficient provision of capacity for passing flood waters caused the destruction of the reservoir dam at the Dells of the Black River in 1911.[7] While the spillway of the lower dam at Hatfield was undoubtedly adequate for normal maximum floods, the sudden discharge of some 14,000 acre feet of water into the lower reservoir, resulted in the water overtopping the earth fill portion of the lower dam. Perhaps 10,000 additional acre feet of storage were released from the lower reservoir, and the resulting flood destroyed the principal business district of the city of Black River Falls, Wisconsin, entailing a large loss of property, though fortunately no lives were lost.

The great flood in the eastern United States in March, 1913, which caused a loss of perhaps four hundred lives and $100,000,000 in the Miami Valley alone, was due to an excessive rainstorm accompanied by other unfortunate physical conditions and so centered over certain drainage areas as to cause an unusual flood state.[8]

These floods demonstrate the lack of fundamental data in regard to the possible extremes of such occurrences, and emphasize the necessity for more extensive investigation and observation of both rainfall and stream flow, and the effect of other physical conditions on these occurrences.

The loss of more than six thousand lives and over $17,000,000 in property in the city of Galveston, on September 8, 1900,[9] due to a West

[7] Black River, Wisconsin, Flood of 1911. Eng. Record, October 14, 1911.

[8] Wabash River Flood, March 21—April 2, 1913, by R. L. Sackett. Eng. News, April 24, 1913.

Recent Flood at Columbus, Ohio, by Julian Griggs. Eng. News, April 10, 1913; see also Eng. Rec. April 19, 1913.

Flood Devastation at Dayton, Ohio. Eng. Rec. April 12, 1913.

Flood of March-April, 1913, on the Ohio River and its Tributaries, by John C. Hoyt. Eng. News, April 10, 1913.

The Ohio Valley Flood of March-April, 1913, by A. H. Horton and H. J. Jackson. U. S. G. S. Water Supply Paper No. 334.

[9] Galveston, Texas, Flood of 1900. The Encyclopedia Americana. Scientific American Compiling Department.

The Lesson of Galveston, by W. J. McGee. National Geographic Magazine, Oct. 1900.

Indian hurricane which drove the water of the Gulf of Mexico over the city, was a serious lesson on the protection of cities from unusual conditions which are not, and perhaps cannot always be foreseen or appreciated. The occurrence of a similar storm in 1915,[10] and the resulting casualties show that Galveston and other cities along the Gulf of Mexico are frequently subject to such contingencies and have not as yet taken the precautions necessary for their safety.

In the last few years, failures in various irrigation projects, due often to inadequate water supplies, have been numerous. In few cases are the facts available, for those who have suffered from such mistakes have usually preferred to bear these losses quietly and not make public the cause of such failures. Only in the case of the work of the United States Reclamation Service are facts of this kind available.

The Hondo Project[11] of the United States Reclamation Service in New Mexico, was designed to take its water supply from the Hondo River. The river has an intermittent flow only, but based upon a study of rainfall records, together with a consideration of the possible runoff due to topographical conditions, the construction was undertaken with the expectation of operating on stored flood waters. The construction was completed in 1906, but since that time the runoff has not been sufficient to allow the storage of enough water for practical use.

In very many cases in the past, public water supply systems have been designed and constructed to utilize supplies of water which have later been found much too limited for the purpose for which they were intended, and expensive changes in the works have thus been made necessary; or such works have been constructed in locations where the supplies have afterwards been found to be polluted and undesirable, with similar expensive results. In a certain city in Illinois, a pumping station was located near a spring which was developed by means of a large masonry well. When pumping began, the well was soon emptied and the inflow was so insufficient that the well and station were abandoned and a new station was constructed in an entirely different locality. In another case, in a city of considerable size, a well was con-

[10] Galveston's Sea Wall Checks Hurricane Devastation, by E. B. Van de Greyn. Eng. Rec. Aug. 28, 1915; see also Eng. News, Aug. 26, 1915, and Sept. 2, 1915.

Effect of Galveston Storm on Sea-Wall and Causeway, by R. P. Babbitt. Eng. News Aug. 26, 1915.

[11] Hondo Project. House of Representatives. Document 1262 (1911). 3d Session 61st Congress.

structed at a large expense into a gravel deposit which furnished a supply adequate in quantity but entirely unsatisfactory in quality. A limited investigation afterwards proved that the gravel stratum underlaid the thickly settled portion of the city and drained the vaults and cesspools of the unsewered area. Such examples were very numerous in the early days of the installation of water supplies, when limited knowledge and experience had not demonstrated the need of study and investigation. They are much too common even now when the experience of the past is available as a warning of the necessity of a full knowledge of these fundamental conditions.

Great losses have been sustained, property ruined, and unsanitary conditions created by the overflow of storm water from sewers and drains of improper design. The records of almost every city will give examples of such occurrences.

Unfortunately for the greatest success of future projects, mankind prefers to publish its successes and to conceal its failures, while frequently much more might be learned from the latter than from the former.

Many of the unfortunate occurrences briefly described above have been due to the lack of investigation and of a thorough understanding and appreciation of the fundamental principles and knowledge of phenomena which it is the province of Hydrology to discuss.

8. Variations in Hydrological Phenomena.—Many of the fundamental phenomena which must be considered in the problems of Hydrology are exceedingly variable in occurrence as regards quantity, intensity and time, much more so, in fact, than the ordinary observer would suspect. It is a common idea that, taking the season through, the average rainfall is not greatly different from year to year either in amount or distribution, yet the rainfall at Madison, Wisconsin, has varied from a minimum of 13.49 inches in the year 1895 to a maximum of 52.93 inches in 1881, and the variation in monthly distribution is still more irregular. A better knowledge of these variations is, however, now becoming common through the valuable work of the United States Weather Bureau.

The casual observer is not apt to realize the great variations that occur in the flow of streams, concerning which he has no means of exact information. His conclusions in regard to stream flow are usually drawn from personal observation, and his observations on subjects in which he has little personal interest are inexact and hence tend to error. Extended and exact observations will show that stream flow

is subject to extreme variations both in drought and in flood, and the limits of these variations are even greater than those of the rainfall on which stream flow so largely depends.

Floods similar to those of March, 1913, in Ohio and Indiana which surpass all previous records, give indications of the possibilities of extreme conditions which may occur beyond any which seem probable from the recorded data available.

The maximum flood must result from the simultaneous occurrence of all conditions favorable to runoff, and it cannot be said, with the limited records of such phenomena, that such simultaneous occurrence of favorable conditions has as yet been realized even in the most extreme recorded case.

The uncertainty of many meteorological phenomena is proverbial. The great variation in the character of the seasons throughout a period of years is very marked. The irregularity in the occurrence of rain and snow, of storms and sunshine, is a matter of common observation. The observer is therefore naturally led to expect that other phenomena, dependent largely or partially on meteorological conditions, will be subject to a similar variation, and be equally uncertain. On the other hand, a few casual observations in which these great variations are seen, might lead to the belief that meteorological phenomena follow no law, or at least follow laws so complicated and involved as to be hopelessly obscure. They might also lead the observer to the conclusion that no ascertainable relation exists between rainfall and stream flow, or between other interdependent hydrological phenomena. Accurate and continuous observations, however, show that while great variations exist, they are limited in character and extent, and that the relations between the various factors of Hydrology and Meteorology, while complicated, are nevertheless fixed and by extended observation can be rendered sufficiently determinate to enable valuable deductions to be based on them. It is most important that the engineer should realize both the great variations which occur in these phenomena and the limitations of such variations.

The engineer is therefore frequently obliged to draw conclusions of greater or less importance, often from very inadequate data, as to the rainfall, the resulting ground water supply, runoff and their possible extremes from some given source or drainage area. In such cases, he may be obliged to estimate the probable and possible rainfall conditions from comparisons with other areas where such data, also frequently inadequate, are available, and which areas are similarly located

geographically, topographically and meteorologically, and where, on account of such similarity of location and conditions, similar intensity and magnitude of rainfall may reasonably be anticipated.

It is readily demonstrable that local conditions are never exactly duplicated and that any comparisons between apparently similar localities are subject to possible errors of considerable magnitude. Hence, estimates of rainfall and runoff, and the design of structures based on such comparisons, must for safety be made with these probable errors in mind and must include factors of safety proportional to the possible errors involved and the serious nature of possible casualties which might result from designs based on such erroneous data.

In considering these problems it is important to recognize the fact that general principles frequently are subject to wide variations, and even to marked exceptions, especially when relating to the complicated subject of meteorology. It is highly essential therefore in assuming that any general principle may or will obtain in a given locality to secure sufficient data to demonstrate that all conditions are favorable to the probable prevalence of such principles and the probable force or intensity of the phenomena resulting thereunder. It must also be remembered that only limited conclusions should be drawn from limited observations. In many cases, conclusions based on data for single months or years would be entirely reversed if based on observations for other similar periods; and both would be altered if based upon the average and extremes shown by long series of observations.

9. Factors of Safety in Engineering Work.—In all engineering work the contingencies to which any structures or plant will be subjected are of necessity more or less indeterminate, and the lack of exact information as to the actual conditions which will prevail, and which will influence the character and usefulness of a structure or plant during its life, require that, in order to provide for such unforeseen conditions, a factor of safety shall be used and that the structure or plant shall be designed much stronger, larger or on different lines than the average condition would apparently make necessary. In the projects of hydraulic engineering, similar factors of safety must be applied as in structural design. In hydraulic calculations, and in the calculations of the volume of flood and of low water flow, no large factors of safety are financially possible, and the supply or capacity of plants or works must be designed for essentially the results desired with only a small margin for safety. It will therefore be seen that, in carefully

made hydrological calculations, the probable inaccuracies are, in spite of the great variations before noted, no greater than in other engineering works, and, although there is much need for extended observations and research, yet the applied science of Hydraulic Engineering is, in exactness, fully abreast with other branches of engineering.

10. **Fundamental Laws.**—Natural laws are always dependable and similar effects always result from similar causes. The difficulty of interpretation lies in the difficulty of differentiating and recognizing the causes to which the effect is due. Successful engineering work is the result of successful differentiation of the underlying facts and principles, and the success of other work based on successful precedent lies in the ability to discern similarity of conditions, or to modify the detail so as to meet the new conditions involved. While the fundamental laws of Hydrology are unchanging, the factors which control their phenomena are so numerous that they result in wide variations in the relations of similar phenomena in different localities. As with all physical phenomena, similar causes, when acting under similar conditions, produce similar results; but the causes, and the varying conditions under which they act, must be carefully investigated and thoroughly understood, in order that the result may be rightly anticipated. With the great variation in the circumstances of occurrence, it is therefore unsafe to apply data obtained from one locality, under one set of conditions, without modifications, to an entirely different locality with radically different conditions, and expect similar results.

The laws of nature cannot be modified by human agencies, but such laws may be utilized under favorable conditions to accomplish results favorable to humanity. A knowledge of the conditions and of natural laws becomes of great importance when such adaptation becomes desirable, and the degree of success assured in the desired adaptation corresponds with the extent of the knowledge possessed and applied.

11. **Complexity of Influences.**—Hydrological problems are frequently difficult to solve on account of complexity of the influences involved. The geological, physiographical, topographical and meteorological conditions vary to considerable extent, with every degree of latitude and longitude, and often with even less extended geographical differences. The meteorological conditions vary as greatly, and sometimes even more greatly with the change of seasons than with the change of locality. Each locality has therefore a combination of conditions more or less different and distinct from those of every other locality, however near or remote, and the laws

which control the occurrence of local phenomena are more or less modified by such local conditions. Hence, the local conditions must be investigated and determined before correct conclusions can be drawn concerning the dependable occurrence of hydrological phenomena.

There are, however, geographical limits within which similar physiographical and climatic conditions prevail, and where hydrological conditions are so similar that conclusions, based on the data of one locality, can be applied, with only slight modifications, to other localities within such limits. If this were not the case, a science of hydrology would be impossible. The greatest difficulties encountered in the study of this subject are these variations and the determination of their effect on phenomena. For accuracy and exact determination, sufficient data are not always available, hence the available data become still more valuable and the extension of these data becomes of great importance.

12. **Sources and Limitations of Hydrological Knowledge.**—Our knowledge of hydrological phenomena is at the present day fragmentary and incomplete. While knowledge in the natural sciences has made great strides in the last two centuries, and our progress in many lines has been phenomenal, the value of a knowledge of the many hydrological data necessary for the satisfactory practice of hydraulic engineering has been but slowly realized.

Rainfall observations have been made in a few isolated cases for perhaps 150 years or more, but anything like a systematic study of rainfall, even in the old countries of Europe, is of comparatively recent date. A few isolated rainfall observations, more or less continuous, were made in America in the 18th century. Several additional stations were established and, although sometimes changed in location, have in this way been continuously maintained since early in the 19th century. By 1850, the number of stations at which such observations were made was considerably increased, and these stations were greatly extended when systematic work of this sort was taken up by the Signal Service about 1870. The most of the precipitation stations have, however, been established since the organization of the Weather Bureau in 1891; but while these stations have already increased in number to 4,971, they are even now too limited to afford data for the satisfactory solution of many problems important to the hydraulic engineer. Where rainfall must be used as a basis for estimating the hydrological conditions for long periods in the future, it is evident that such data should be available for long periods in the past, and the com-

paratively recent establishment of present stations, therefore, makes it clear that our knowledge in this regard is much too limited.

On the subject of streamflow the data are still more incomplete. The measurement of flowing water is more difficult than the measurement of rainfall, and in very few cases have reliable observations of the flow of any stream been continued for half a century. About 1893, the United States Geological Survey began to accumulate data and to make observations on the flow of streams, and the published reports of the Survey are the principal source of information from which such data can be obtained. Owing to financial limitations, the extent of these measurements and observations is far more restricted than those of rainfall, and the stream flow in many locations and many streamflow conditions remain essentially unknown and are still to be investigated.

In this connection the stream gage height observations collected and made public by the Weather Bureau afford valuable data from which, by comparison, more limited observations can sometimes be extended.

Geological data from which hydrological conditions of underground water sources may be studied, have been accumulated rapidly in the last twenty-five years and are found in the numerous volumes published by the United States Geological Survey and by the geological surveys of the various states.

The development of all of these branches of knowledge goes hand in hand with civilization and has been extended as settlement has extended and as the prospective demand of civilization has pushed the frontier of knowledge farther and farther into hitherto unknown regions.

The work of the hydraulic engineer is frequently required to make settlement possible, hence in many cases hydrological problems arise in regions where such investigations have never been made or have only just begun. The difficulties that arise in such cases must be known and appreciated in order that the work of the engineer may be conducted on conservative lines and result in developments whose accomplishments will assure the success and permanency of social dominion over the new lands.

13. **Determination of Hydrological Relations.**—In considering the involved question of hydrology it is most important to disabuse the mind of personal bias and to leave it as free as possible to form conservative and logical conclusions from the best data available.

It is a common experience that many men formulate an hypothesis

and gather data to prove it instead of first collecting the data and formulating an hypothesis therefrom. With sufficient bias almost any conclusion can be reached to the satisfaction of the prejudiced investigator. All correct hypotheses must rest upon either or both inductive and deductive reasoning, and to the extent that the hypothesis fulfills the requirements of both methods it may be regarded as correct.

Inductive reasoning consists in establishing a general law on many observations in which a certain effect is found to follow a certain cause. This process depends fundamentally upon eliminating so far as possible other contributing causes so that the effect in question may correctly be attributed to the one contributing cause. As the factors become complicated, the results of such investigations become uncertain and can finally be demonstrated in a satisfactory manner, if at all, only by extended investigations and when the main cause is so predominating as to produce an effect in spite of other complicating factors. If, for example, it is desired to investigate the relations of annual evaporation from soil to annual rainfall (see Sec. 74), the results of a long series of observations, under conditions where other factors are as similar as possible, are platted with annual evaporation and annual rainfall as ordinates and abscissas respectively and the relations of these platted points are observed. (See Fig. 85, page 140). If the annual evaporation were essentially constant, regardless of the variation in annual rainfall, the observations would fall approximately on a horizontal line representing the mean annual evaporation. If, however, the annual evaporation increases with rainfall, as seems to be true, such fact will be indicated by the relative location of the points on the drawing; and if the centers of gravity of the higher and lower groups of points respectively be determined, the location of such centers of gravity will indicate the direction of an inclined line which will more clearly represent the mean annual relations of evaporation and rainfall. It will be noted from Fig. 85 that for the two years in which rainfall was 23.5 inches, the evaporation was 13.9 and 22.2 inches respectively. This would seem to indicate that the general hypothesis is incorrect. The departures of the various observations from the line of mean annual relations so established do not, however, indicate that the hypothesis is incorrect but they show that other factors are present which frequently so influence and obscure the relations of the two factors considered that they may frequently overcome the general relations established.

The relations of various factors in different phenomena may be in-

vestigated in a similar manner and experimental curves[12] established showing the relations found which may be reduced to formulas more or less broadly applicable. The ultimate truth of any hypothesis advanced or of any formula proposed is confirmed when it is always found to apply to extended series of observations in the investigation of which it can be consistently employed. Relations so determined are both quantitative and qualitative and are therefore of the greatest use to the engineer as a basis for his conclusions.

Deductive reasoning is based on well established fundamental principles that are known to obtain from previous experiences. From these fundamental principles a certain effect is clearly deduced as a consequence of a certain cause. From such deduction, coupled perhaps with other fundamental principles, other results are found necessarily to obtain and the same process is extended until the ultimate conclusions are reached. Here too the process of reasoning is complicated by involved conditions which frequently lead to serious error unless every step is closely scrutinized. Deductive logic is the basis of all sciences and its methods are rigidly exact if correctly used. In hydrological problems the results of deductive reasoning are usually qualitative rather than quantitative.

In complicated problems of hydrology, the investigator needs the aid of all possible logical methods, and even where every method of logic is applied it is frequently found that on account of limited or incorrect data and lack of knowledge of certain fundamental principles involved, the relations sought can by no means be definitely established. Indications may lead to certain general conclusions, and while such conclusions may be inexact they may be the best possible from the experience and knowledge at hand. Under such conditions any conclusions must be regarded as tentative only, utilized with caution, and final conclusions must be withheld pending broader observation and more extended experience.

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[12] See Empirical Formulas, by Prof. T. R. Running. John Wiley & Sons, Inc. 1917.

Practical Mathematics, by Prof. F. M. Saxeby. Longman-Green Co., 1905, Chap. VIII.

Methods for Determining the Equation of Experimental Curves, by H. S. Landsdorf. Jour. Asso. Eng. Soc. Vol. 32, p. 325, 1904.

Determination of Experimental Equations, by L. F. Harza. Wisconsin Engineer, Dec., 1908.

14. **Danger of General Conclusions.**—In considering many of the simpler phenomena, the relations between cause and effect are so direct as to be readily understood and appreciated. The very simplicity of such relation is apt to be misleading when more complex phenomena are under investigation and, in consequence, undue weight is often given to some single influence that may be only one of many which modify or control the results under consideration.

By complex phenomena are meant those in which the effect is modified by numerous causes, each influencing the ultimate result not only in accordance with its own character and intensity, but also in accordance with the relative character and intensity of other co-ordinate influences. The effect in such cases may be regarded as the resultant of numerous factors, and the weight, importance and effect of each must be carefully differentiated in order that its relative importance may be rightly understood and clearly appreciated. Most meteorological and climatic problems are of this class; and many such problems are so involved in character, the factors that modify their occurrence are so complicated and so irregular, and they are often so modified by unappreciated, and perhaps by unknown causes, as to make their occurrence appear to the limited vision of the casual observer as devoid of law and beyond the possible knowledge of mankind.

The first common error in the consideration of such problems is the assumption of a simplicity of the relations between cause and effect that is not warranted by fact. The second common error is the assumption that when a certain cause is operative under one set of conditions that it is operative to a similar degree under all other conditions. The third common error is due to the confusion of cause and effect, or in attributing the cause to the effect instead of the true relation of the effect to the real cause.

The rapid advance in fundamental science and the development of many startling and hitherto almost unknown phenomena, applicable perhaps to new commercial development have, in cases, given the unwary a basis for a belief in possibilities not yet developed, and in many cases, most improbable. This readiness of the public to anticipate great advancement in scientific achievements has been utilized by psuedo scientists to advance immature ideas as though they were established principles and to make unsubstantiated claims for personal or class reasons. In many cases such claims are advanced in good faith, based on only a partial examination of all the data of the problem.

There are those who, even in the face of the vast number of almost

unstudied influences that control the weather conditions and the almost insignificant data yet available, still believe in the present possibilities of long advanced weather predictions.

The foresters and their friends see in the planting of trees, which is only one of manifold active influences, the solution of flood troubles and low water conditions. Others, reasoning from cause to effect, assert material increase in precipitation to be due to forests or irrigation; and in manifold other lines, marked influences on extended phenomena are declared due to limited developments in one of many controlling factors. The engineer must not be misled by psuedo-scientific argument. His analysis must be complete, his conclusions conservative and limited to the case at hand to which his data apply; and even in extending his personal experience from one field to another, he must keep in mind the new factors which may always be present and which must modify the conclusions which, under other conditions, he has known to be definitely established.

Experience is a most important teacher, and much of the knowledge of greatest value in practical life is acquired only by this means. Where certain local conditions in various parts of the world or even in the same country differ greatly, conclusions based on the conditions of one locality must be applied to any other locality only with great care. For example the ice conditions of the Arctic and Antarctic regions give rise to climate and physical conditions which are not fairly comparable with temperate regions where ice is a seasonal phenomenon. Rainfall in one country, or even in a part of the same country, may be well distributed for agricultural purposes, while in another location even a greater annual rainfall may be so distributed as to occasion a serious shortage of moisture during the seasons of plant growth. Again, geological and topographical conditions may make certain phenomena largely local both in quality and intensity, and produce results from such causes which will be greatly different or absent altogether under radically different conditions.

The relation of the rainfall to the amount and distribution of water flowing from any given drainage area is a complicated problem. The flow from an area is so directly dependent on the rainfall thereon that it seems some simple and constant relation should be ascertainable between the quantities of each. A brief investigation, however, shows that the modifying conditions are manifold and that the relative importance of each influence varies even more widely than the apparent range in the conditions. These influences are so numerous, and their

modifying effect on one another is so direct and important, that no general and constant relation exists between any one influence and the ultimate results. These facts have led to many misinterpretations and erroneous conclusions in the attempt to establish simple relations which from the nature of the case cannot exist. Many serious errors and resultant losses have been occasioned by the adoption of general conclusions, based perhaps on an accurate analysis of one series of local conditions, but applied under other conditions where such conclusions were not at all applicable.

Conclusions from hydrological data must therefore be adopted with caution and should generally be confined to limited localities until experience warrants their extension to wider fields.

15. Purpose of the Study of Hydrology.—The purpose of the study of Hydrology is primarily to acquire a knowledge of the extent and limits of the variations in hydrological phenomena, to ascertain the effects on such phenomena of the various physical conditions that obtain in any locality, and to investigate the geographical limitations within which the observed phenomena may be applied with greater or less modifications, also to establish as far as may be, such laws as will aid in the determination of the effects to be expected from other physical conditions which are found to obtain. For these purposes the study of Hydrology must include:

First: The study of the general physiographical, geological and topographical features of the earth, the factors that have produced and are now modifying such features, and their general hydrological relations.

Second: The study in a more specific way of these physical conditions and factors in relation to the area of the country to which the practice of the engineer will be largely confined.

Third: The study in still greater detail of the hydrology of certain localities where certain important laws or relations are found to be best exemplified.

It is the further purpose of this text to emphasize more particularly those lines of hydrological study that are most important, and the necessary and desirable direction in which hydrological investigation and study should be extended.

16. Study of Hydrological Literature.—Only a brief examination of the subject of Hydrology is necessary in order to appreciate the complexity of the subject and the extent of the field which must be examined in order to secure the data to demonstrate the principles on which its application must rest. It at once becomes apparent that a

single treatise can do little more than point out the main underlying principles, and illustrate the same with a few general data which will indicate the direction and extent of the variation which must be anticipated and the character of the further investigations needed in the solution of local problems. In the actual application of these principles to practical work it is evident that they must be studied in the light of a detailed knowledge of local circumstances and conditions, and that in every case those principles which are to be directly applied must be considered in much greater detail than can possibly be done in any single volume. It is not the hope of the author to offer a complete treatise on this subject to the student or engineer, but only to point out the general relations that have been established, the general principles that are involved, and the necessity that exists for further research and study before any concrete problems can be solved even approximately.

There is now in existence an extensive literature on various hydrological subjects, otherwise this book could not be written. While confining these pages to a brief consideration of the fundamental principles on which Hydrology rests it has also been the purpose of the author to point out, so far as possible, the source of the data which have been utilized and the further sources of information which are available for a more complete study of the various phases of the subject. In the solution of any concrete problem, the various publications which are noted in the list of literature following each chapter must be consulted in detail, and conclusions offered by the author should be accepted only so far as the data on which they are based seem to warrant. As noted in Section 14, general conclusions must be accepted with care and applied only when fully substantiated by all the local data which are available. Only by the greatest care can the correct conclusions be drawn for any specific hydrological problem, and even conclusions so reached are subject to various uncertainties. The broadest investigation and study are essential to a sound conception of the various problems which the engineer must meet.

17. **References to Failures in Hydraulic Engineering Works.**— The student or reader should study one or more of the following failures, and prepare a statement concerning the cause and results of the failure, and the nature of the information which should have been acquired or investigation which should have been made in order to have assured success.

1. Johnstown, Pa. The Johnstown Disaster. Eng. News, June 1, 8, 15, 22; July 13; Aug. 17, 1889.
2. Austin, Texas. Failure of Masonry Dam. Eng. News, Feb. 22; April 12, 19; May 10; June 21, 1900; Eng. Rec. April 14, 21; May 26; June 9, 30; July 28, 1900.
3. Fishkill, New York. The Failure of the Melzingah Dams of the Fishkill and Matteawan Water Company. Eng. News, July 22, 1897.
4. St. Anthony Falls, Minn. Effects of Mississippi River Floods on the New St. Anthony Falls Dam at Minneapolis. Eng. News, May 13, 1897
5. Minneapolis, Minn. Failure of a Minneapolis Dam by Ice Pressure. Eng. Rec. May 13, 1899; Eng. News, May 11, 1899.
6. Collingswood, N. J. Standpipe Failure. Eng. Rec. Jan. 20, 1900.
7. Elgin, Ill. The Failure of the Standpipe. Eng. News, May 3, 1900.
8. Providence, R. I. The Failure of Two Earth Dams. Eng. News, March 21, 1901.
9. Jeanette, Pa. The Failure of the Oakford Park and Fort Pitt Dams. Eng. News, July 23, 1903; Proc. Engrs. Club of Phila., July, 1904.
10. Cobourg, Ontario. Damage by Ice to a Standpipe. Eng. News, Aug. 18, 1904.
11. Phoenix, Ariz. Construction, Repairs and Subsequent Partial Destruction of the Arizona Canal Dam. Eng. News, April 27, 1905.
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13. Fergus Falls, Minn. The Failure of the City Dam. Eng. News, Oct. 14, Nov. 3, 1909.
14. Pittsfield, Mass. The Undermining of a Reinforced Concrete Dam. Eng. News, April 1, 1909.
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22. Black River Falls, Wis. Failure of the Dells and Hatfield Dams and the Devastation of Black River Falls. Eng. Rec. Oct. 14, 21, 1911; Eng. News, Oct. 19, 1911.
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24. Ohio River. Failure of Dam No. 26. Eng. News, Aug. 22, 1912.

25. Ontario, Canada. The Failure of the Dam of the Erindale Power Company. Eng. Rec., April 27, 1912.
26. Winston, N. C. The Failure and Repair of the Winston Water Works Dam. Eng. News, April 11, 1912.
27. Port Angeles, Wash. Washout of Base of Port Angeles Dam. Eng. Rec. Nov. 30, 1912.
28. Dam and Embankment Failures in 1912. Eng. Rec. Apr. 19, 1913.
29. Stony River, W. Va. Break in the Stony River Dam. Eng. News, Jan. 22, 1914; Eng. Rec., Jan. 24, 1914; Jour. Engr's Soc. of Penn., Apr. 1914. The Reconstruction of the Stony River Dam. F. W. Scheidenhelm. Trans. Am. Soc. C. E., Vol. 81, 1917, p. 907.
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31. California. Wreck of the Otay Rock-Fill Dam. Eng. Rec. Feb. 12, 1916.

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CHAPTER II

WATER—ITS OCCURRENCE, UTILIZATION AND CONTROL

18. **Importance of Hydrological Conditions.**—The conditions of the occurrence of water have an important influence on the development of every country. A closer analysis will show that the occurrence and conditions of waters have even a more important influence than has previously been indicated.

Water is and always has been one of the most important, if not the most important, of the agencies of topographical and geological change. To a greater or less degree it dissolves almost every form of mineral matter from the strata, which action is accelerated by the chemical activity of matter held in solution and by increased temperatures. Its expansion as it changes to ice by reason of low temperatures is a powerful mechanical agency of disintegration. Its erosive effect in its flow from the mountains to the sea, aided by the detritus carried with it, has been a most potent agent in topographical development, and the deposition of materials transported to lakes and seas has been a most important agent in geological growth.

Without water organic life cannot exist. It is therefore one of the prime necessities of all organic life, and it is the largest constituent of all animal and vegetable matter. Its action as a solvent is here again a most important property in both animal and vegetable physiological processes. About two-thirds of the average human food is liquid. The average adult requires about 4½ pounds of simple liquid each day, with about 2½ pounds of solid food, which is about half liquid, intimately commingled with solid matter. Nutriment and oxygen are taken up and distributed to the various tissues of the animal body by the agency of the blood, which is ninety per cent. water, and which also removes the waste products from the system. Vegetation is equally dependent upon water for the solution of food, its distribution to the vegetable tissue, and the removal of waste.

Water is not only necessary for the existence of life, but its occurrence and condition have a marked effect on health. A super-abundance may destroy or be seriously detrimental to both plants and animals, and its character as influenced by the matter held in solution or carried in suspension may also have a serious effect on health. Water

draining from settled regions often receives and transports organisms which are prejudicial to the health of man if the water so polluted is

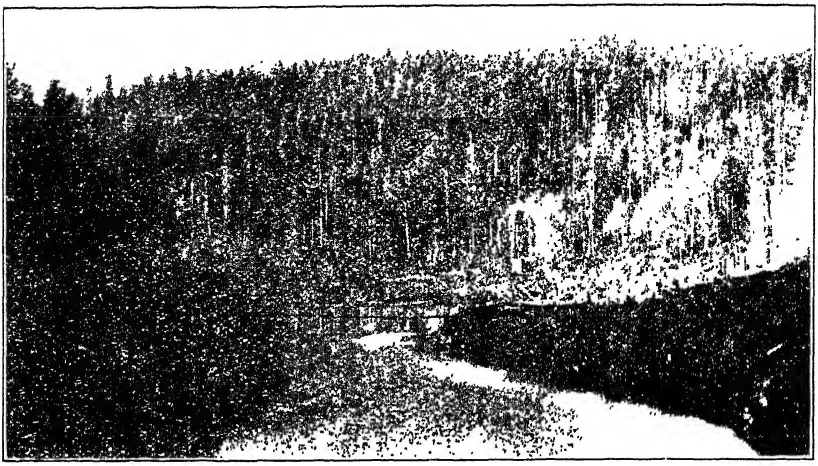

Fig. 1.—Forest in the Olympic Foot Hills near Port Angeles, Washington. Annual Rainfall about 40 Inches (see page 25).

Fig. 2.—Buckhorn Prairie Desert in Central Utah. Sage Brush in Foreground. Annual Rainfall about 12 Inches (see page 25).

utilized for dietetic purposes. Water on account of its high solvent and transporting qualities, is constantly removing matter from the drainage area on which it falls and transporting it to other regions where it may

be either beneficial or detrimental. In some irrigated regions the introduction of water has made possible successful agriculture, but a too lavish use has frequently brought alkalies to the surface to the detriment of plant life, or has turned the desert into a swamp on which agricultural products can no longer be grown.

For successful agriculture, about 24 inches of annual rainfall, properly distributed through the season, seems to be essential unless an artificial supply of water is provided. About 15 inches of rainfall per year is required for vegetation, and the remainder of the rainfall is dissipated in other ways. For intensive cultivation, an additional supply can be used to advantage. Where less than 24 inches of rainfall is available irrigation becomes desirable, and with a considerable decrease becomes highly essential (see Figs. 1 and 2, page 24).

Water has always afforded an important means for transportation. For foreign commerce and for domestic commerce between points on the coasts and between points on the Great Lakes, navigation offers the most economical method of transportation of bulky materials. In the early development of modern civilization and prior to the evolution of railways, river navigation was highly important. In undeveloped countries, internal navigation is still the most important means of transportation (see Figs. 3 and 4, page 26). Even with railways well developed, river navigation may be found more economical than transportation by rail where a permanent market requires the constant movement ot a large amount of bulky freight between river points. Under some conditions, artificial waterways or canals have been found desirable and economical, but they have become less important with the development of railway transportation. Canals for large vessels are feasible only when limited:[1]

First: To comparatively short connections between large and important bodies of water between which large traffic would naturally exist except for rapids or other natural barriers, as in the case of the Sault Ste. Marie Canal between Lake Superior and Lake Huron.

Second: To comparatively short canals which save a very great sailing distance, as in the cases of the Suez and Panama Canals.

Third: To short canals connecting the sea with large commercial centers, as in the case of the Manchester, England ship canal.

The competition of long lines of canals with rail transportation is however no longer feasible under modern commercial conditions.

[1] Preliminary Report of U. S. National Waterway Commission, (Washington, 1910), p. 13.

FIG. 3.—Boats at Gang Yuen, China. Transferring Salt on the Grand Canal (see page 25). (S. T. Suen.)

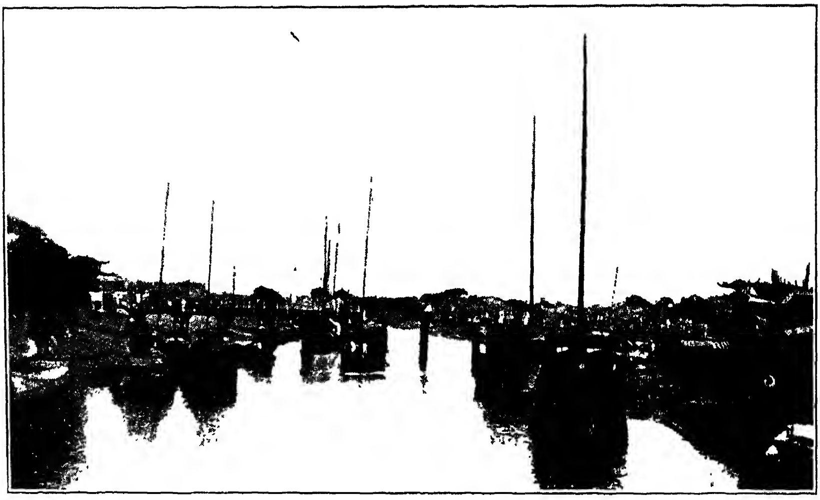

FIG. 4.—Boats on the Grand Canal near Tsingkiangpu, China (see page 25).

Transportation by means of navigation canals and rivers has lost the relative importance which it attained in the early history of commercial development.

Water is also important as a source of power. It was of the highest importance in the earlier days of the development of our civilization

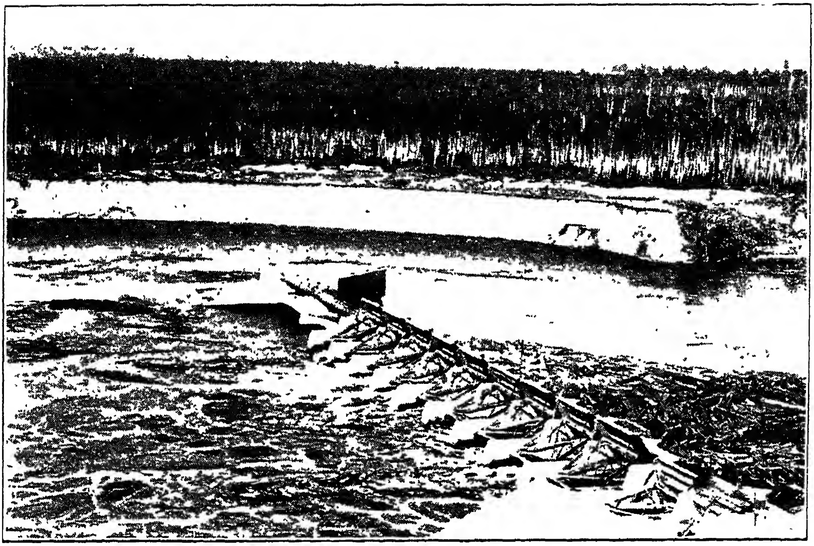

FIG. 5.—Washout around End of Marathon Dam, Rothschild, Wisconsin. Flood of October, 1911 (see page 28).

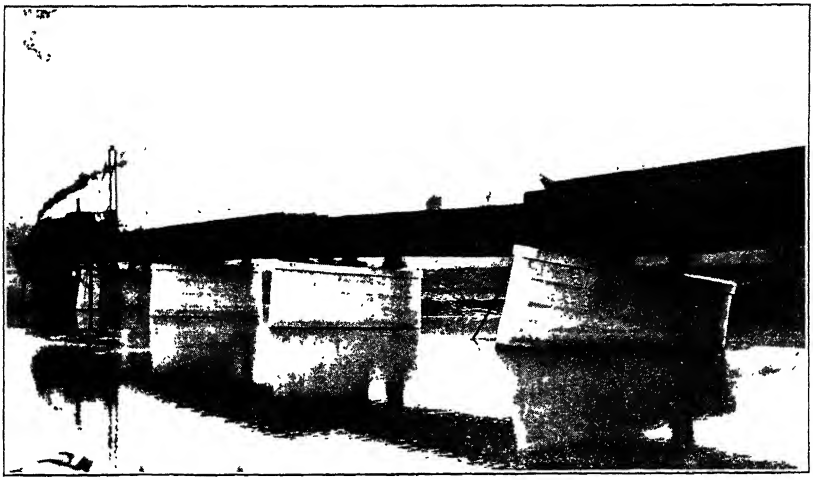

FIG. 6.—Bridge Piers of Big Four Railroad near Miamisburg, Ohio. Undermined and Part of Bridge Destroyed by Flood of 1913 (see page 28).

prior to the evolution of the steam engine, and frequently was one of the most important factors in determining the location of manufacturing industries. With the development of the steam engine, the advan-

tage of a location near large centers of population or near lines of transportation overcame differences in the cost of steam and water power and the value of water power began to decrease. The development of large industries also rendered the small water powers of little value, and many which were developed and utilized at an early date were later abandoned. In late years electrical transmission and the use of electric current for light have given a new impetus to the development of water powers and made available at manufacturing centers many powers which could not previously be used to advantage (see Frontispiece).

Water in certain phases of its occurrence becomes a serious menace to life and property. Surface waters under flood conditions and through the same characteristics that are productive of topographical and geological changes, endanger engineering structures constructed in their path, and through the destruction of such structures and on account of unusual volume and consequent height and velocity, imperil human life and property during such periods (see Figs. 5 and 6, page 27).

19. **The Occurrence of Water.**—In a relative sense, the irregularity of the earth's crust is slight; the maximum elevation of the highest land is about 5.5 miles above sea level, and the greatest depth of the ocean is about 6 miles. The maximum variation in elevation, therefore, is only 14/100 of one per cent. of the earth's diameter, which is sufficient however, to raise somewhat more than a quarter of the earth's crust above the ocean.

The exact relations of the area of land and water are not definitely known, as the Polar regions have not yet been fully explored.

The total area of the globe is about 197,000,000 square miles. Of this the land occupies somewhat more than 50,000,000 square miles. About six-sevenths of the land area is situated in the northern hemisphere of which it occupies about one-half of the total area, while in the southern hemisphere only about one-fifteenth of the area is land.

Besides its occurrence in oceans, seas and the many inlets to the land connected therewith, water is found in various depressions in the earth's surface above sea level, where it collects and forms lakes, often of considerable extent, frequently connected by overflow channels with the sea to which the surplus waters flow. Occasionally, however, these lakes and island seas have no outlets because the waters collected are not sufficient in quantity to raise the surface of the lakes to the height necessary for overflow.

FIG. 7.—Swamp in Southeastern Missouri. Little River Drainage District. Annual Rainfall about 45 Inches. (W. A. O'Brien).

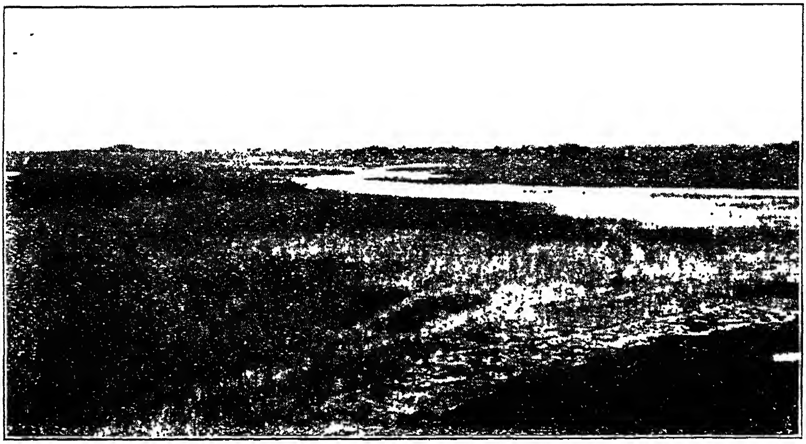

FIG. 8.—The Everglades of Florida. Annual Rainfall about 55 Inches. (Leonard Metcalf).

In many cases the depressions are so shallow that aquatic vegetation occupies much of the area and such bodies of water are classified as swamps and marshes (see Figs. 7 and 8).

In many other cases, the depressions in the surface of the earth are elongated troughs in which water gathers as rivers and streams, and

through which it flows from the higher lands to the lakes and to the oceans. In the extreme north and south are found great fields of snow and ice which are, from the limited view of human life, perpetual and which annually extend their areas far into the temperate zones during the winter season, withdrawing toward the poles with the advent of summer.

Many of the geological strata, such as the sands, gravels and sandstones, are highly pervious. The limestones are occasionally cavernous, and most of the harder non-porous rocks are cracked and fissured, frequently for many feet below the surface. Into the cracks, fissures and caverns and into the structure of the pervious deposits, the surface waters sink by gravity and slowly flow toward lower levels, when there are outlets at such levels as permit the water to discharge into the streams, lakes or oceans. Otherwise these rocks become and remain filled until some opportunity of discharge occurs. Such waters are classed as phreatic or subterranean waters and give rise to geysers, springs and artesian wells, and to deep and shallow non-flowing wells.

The source of most phreatic waters and of all the waters of lakes, swamps, marshes, rivers and streams, is the rain or snow which falls in various quantities and at various times and seasons on the drainage areas from which such waters flow.

20. **Circulation.**—The waters of the earth are always in motion, and circulate in various systems more or less separate and distinct. The waters of the oceans have a circulation produced by difference of temperature, by the rotation and revolution of the earth with respect to the sun and moon and the relative attraction of these bodies, and by the motion of the earth's atmosphere. These various influences result in currents, tides and waves. Atmospheric movements, temperature changes and other physical conditions give rise to evaporation, transportation and precipitation. The water precipitated on the land as rain, snow, dew or fog is again partly evaporated and part enters the water courses or seeps into permeable portions of the land surface and again seeks to return to the sea by virtue of gravity. It is in consequence of these systems of circulation of the hydrosphere that life on the globe is rendered possible, that the utilization of water for human betterment becomes feasible and that, on the other hand its occurrence is often inimical to the interests of mankind.

The causes of the circulation of water on the earth's surface may be more systematically reviewed as follows:

First.—The waters of the ocean, heated at the tropics and cooled at the poles, have a motion toward the poles at the surface, and from the poles in the lower portions of the sea.

Second.—The difference in velocity of rotation between equatorial and polar regions affects the flowing waters and gives the warm surface currents an easterly direction against the westerly continental shores. These currents are modified by continents, continental irregularities, islands, and the larger rivers.

Third.—The attraction of the sun and moon on the ocean and other large bodies of water produces the tides which follow the lunar revolution until they break on the eastern continental shores and then flow back, vibrating synchronously with the lunar revolutions.

Fourth.—The friction of atmospheric currents on the water produces waves which at times of storm break with great force on exposed portions of the land.

Fifth.—A constant evaporation goes on from all water surfaces. This is increased: *a.* By increased temperature. *b.* By the removal of vapor by movement of atmospheric currents. The vapor so formed rises into the upper atmosphere which when cooled becomes super-saturated and the moisture is precipitated as rain or snow.

Sixth.—The rainfall and melted snow follow various courses: *a.* A portion is re-evaporated and passes into the atmosphere. *b.* A portion is utilized in plant growth or in plant transpiration which again reaches the atmosphere. *c.* A portion seeps into the strata, and following their dip, finds its way ultimately into the rivers and seas. *d.* A portion flows over the surface into the water courses and thence to the sea.

Seventh.—In the polar regions and in high mountain altitudes, precipitation takes place as snow and the temperatures are so low that melting occurs in a comparatively small degree or not at all. The resulting vast accumulations of snow exert a pressure sufficient to form ice masses in their lower portions, which, from the super-imposed weight, are pressed outward until their glacial terminations either melt in the lower altitudes or reach the sea and are melted or broken off as ice bergs.

The action of all these various factors which control the circulation of water on the earth is modified by the local physical and meteorological conditions.

21. **The Cleansing and Transporting Work of Water.**—Water has been termed a "universal scavenger." As it condenses in clouds and is precipitated as rain, it cleanses the atmosphere of suspended matter, organic or inorganic dust and germ life, sufficiently light to be carried into the atmosphere by wind currents and which are found at all heights. After a long dry period, the rain that falls over a large city is highly polluted, while in the country districts, far from the smoke and dust of cities, the rainfall is more nearly pure. Rainwater therefore reaches the earth in a more or less impure state, and the earlier rainfall is commonly most greatly polluted by such impurities. After it reaches the earth, it continues its cleansing action. It dissolves some of the soluble matter with which it comes in contact, and takes up and transports materials which it does not dissolve. The amount and character of the dissolved and transported material depend upon the character of the material with which the water comes in contact, the duration of the contact, and the volume and velocity of flow. If it falls on indurated areas, which are only slightly soluble, and cannot be eroded easily, it flows away "soft" and clear. Such water may be comparatively pure and free from sediment. Falling on disintegrated strata or areas covered by glacial drift, the water frequently becomes more highly impregnated with mineral salts and is known as "hard water." In rapidly flowing streams the waters are frequently turbid, especially during the high velocities of flood flows.

When waters seep into the strata, on account of longer and closer contact, they take into solution even greater amounts of salts than are found in the surface waters, and the character of such dissolved materials depends on the nature of the deposits through which they flow. They sometimes become highly saturated with mineral matter which is increased in quantity by the agency of dissolved gases, principally carbon dioxide (CO_2), and such waters when they reach the air through fissures or bore holes as springs or wells, frequently lose the dissolved gases and deposit the surplus matter which they can no longer hold in solution.

The mineral matter so carried is sometimes unfavorable to both vegetable and animal life, but the most common impurities detrimental to man are the organic impurities which are carried by the surface waters and sometimes also by underground waters and which have been taken up from areas polluted by animal life.

With the exception of some of the mineral spring waters, most of the natural waters were originally potable and offered to the early

settler sources of supply at once obvious and ample. Settlement has wrought a rapid change in these waters. Where the population is still small and scattered waters are still pure and satisfactory for domestic use, but along the streams where the larger cities are situated and in all thickly inhabited localities the increase of population has brought its unfailing results in a greater or less degree. The wastes of manufacture, the sewage of cities and other refuse products of civilized life have found their way into the streams, seriously contaminating them. The ground waters are tainted with the leachings of surface filth and of underground vaults and cesspools, and in many cases while apparently not offensive are nevertheless menacing to public life and health by the ready means they offer for the transmission of certain forms of diseases. As population increases, the danger of the presence of these organic poisons in surface waters also increases and with a dense population becomes almost a certainty. The same may be said of ground waters but in this case the contamination, being hidden from sight, is still more dangerous. A public nuisance which pollutes a stream is usually quite obvious on inspection; a leaching cesspool however may present a respectable surface appearance while filling the ground waters with filth and corruption, and the neighboring wells with the specific poisons or germs of the most fatal diseases.

22. **Precipitation.**—All waters which occur above the ocean level clearly result from and are renewed by precipitation, and must of necessity vary in amount as the precipitation varies. While there are other important modifying factors that influence and control the occurrence of these waters, precipitation is of greatest importance, for without it these waters would not exist. This is evident in many parts of the earth where little or no water is found on account of the almost total absence of precipitation.

Various parts of the earth experience all gradations of precipitation from the condition of no rainfall to the other extreme found within the equatorial belt where torrential rains are of daily occurrence. Even within the limits of a comparatively small territory, the rainfall conditions vary widely both in quantity and distribution, and when these, together with the similar variations in other physical conditions are considered, the consequent variation in both surface and phreatic waters is apparent. Not only is there a great variation in average quantity, intensity and seasonal distribution, but in every locality there is likewise a great variation in the annual and seasonal amounts. Even the desert places are sometimes subject to intense local rains,

which may occasionally during a course of years visit locations ordinarily devoid of rain.

In every locality the annual rainfall is subject to considerable variation, but the seasonal fluctuations are still more extreme, and the smaller the division of time considered the more radical such differences become. In hydrological study these extreme variations become of great importance for they modify the conception of every hydraulic problem involving either the utilization of, or the protection against the waters of streams and strata.

23. **Surface Waters.**—It is evident that the surface waters are more widely distributed, greater in quantity, of higher utility, a larger source of danger and disaster, and therefore of more importance than the underground waters which are often only of local occurrence. The surface and subsurface waters have, however, certain inter-relations and certain independent relations. In their inter-relation they must be discussed in common, but in their independent relations they require independent treatment. The surface waters therefore being of widest importance and utility need more extensive consideration and treatment.

In considering the subject of circulation it has been noted that in general surface waters are derived from precipitation as rain or snow. A portion of the precipitation under ordinary topographical conditions flows over the lands and finally reaches more or less well defined stream channels through which it flows by gravity until in general it finally reaches the ocean. This portion of the precipitation is technically known as runoff or stream flow. Another portion of the precipitation is taken up by vegetation and utilized in plant growth; still other portions are evaporated and, together with the larger portions of that taken up by the plants, finally add to the atmospheric moisture. Under favorable circumstances, still another portion sinks into the ground and is the source of underground waters which either remain in the strata or ultimately add to stream flow or flow into the lakes and the oceans. It is self-evident that there must be an inter-relation among the various quantities of water that are used in the various ways mentioned. That water which is evaporated, utilized by plants or which seeps into the ground must limit the amounts that occur as runoff, and conversely every factor that affects one of these methods of disposal must also affect all others. Under favorable conditions, plant life and evaporation are most active and commonly receive and utilize the earlier portions of rainfall, especially when such rainfall is small in amount.

Pervious soil and rocks next secure their proportion and only after their demands are satisfied so far as conditions will permit, do the remaining portions flow away over the surface. Even then evaporation and seepage may still be active throughout the entire flow to the sea. The seas are in general great reservoirs into which the streams finally deliver those portions of the rainfall that are not lost in evaporation or seepage, and in general they are the ultimate destination of most of the seepage waters.

For water to exist permanently in areas below sea level there must be:

1. An outlet or inlet to the areas from the ocean which is below ocean level and through which the area may be fed by the ocean; or there must be

2. An adequate drainage area which will furnish the depressed area with enough water to offset evaporation and supply plant life (if such exists). The water surface will be maintained at an elevation either at the elevation of the outlet from which the water will overflow or at varying elevations at which evaporation from the water surface will balance the inflow.

For water to exist in areas above sea level as seas, lakes, ponds, swamps or marshes, there must be a depression below the outlet of the basin or the areas must have very little gradient. The water area must be fed by a drainage area which will furnish sufficient water to supply evaporation, plant life and seepage, and maintain the water level at varying elevations which may or may not produce overflow.

For water to exist in streams, there must be a sufficient precipitation to provide for plant life, evaporation, seepage and the runoff of the stream.

24. **Ground Waters.**—All geological deposits are more or less pervious and water under the action of gravity forces its way wherever rock structure will admit of its presence. When the structure is fine or the pores between the particles small, water passes slowly; through open cracks and fissures and through very porous material it moves with considerable velocity, and through its quality of solution it sometimes dissolves the rock structure and creates for itself channels of considerable size. In the main, however, its occurrence is in the form of sheets of greater or less magnitude in the gravels, sands and sandstones, which sometimes underlie areas of large extent.

These phreatic waters are replenished directly or indirectly from the precipitation at the points where they approach the surface. These waters constitute the largest factor in maintaining the low water flow

of streams and are frequently conducted to considerable distances and delivered into water courses from springs where cracks or fissures afford an outlet. Frequently they are discharged into lakes, and often directly into the ocean.

Under some conditions, the water received into these deposits at a comparatively high elevation, is conducted between impervious layers under lower lands where its pressure is sufficient to bring it to the surface in springs, if cracks occur in the overlying deposits, or as artesian wells if the superincumbent strata be pierced by the drill.

Where the path of the subterranean water is intersected by wells or by shafts, the water of the strata flows into such excavations and rises to the local hydraulic gradient of the strata. Under such conditions it will afford a more or less abundant water supply, according to the nature and extent of the water bearing deposit, and of a quality dependent on the nature of the strata through which it flows. In the same manner these waters enter into excavations, shafts and mines constructed into or below the water bearing deposits, and cause a considerable expense either in the cost of excluding such waters from entry or in the cost of their removal by pumping. They frequently saturate an entire stratum and create a severe flood condition which may cause motion in the strata itself where the normal structure has been modified by excavation. This condition gives rise to land slides such as occur in the railroad cuts and such as have caused much trouble and expense in the deep cuts of the Panama Canal.

Phreatic waters are sometimes available for public and private water supplies, irrigation, and in rare cases for power.

In certain cases the condition of an unsaturated pervious subsurface deposit overlaid by an impervious soil with resulting swamps or marshes, may be obviated by draining the overlying waters through outlets into the pervious deposits, thus reversing the ordinary conditions. As drainage waters usually carry considerable silt, the results of such drainage methods are usually short-lived except for limited capacities or under unusual conditions.

25. **Water Supplies.**—Not only is water necessary for the existence of animal and vegetable life, but such water must have a certain character or it will not serve its purpose. Potable water or water which is not prejudicial to health when used as a source of domestic supply, must be free from the germs of disease, and it must also be free from injurious kinds and quantities of vegetable matter and of inorganic salts.

The effect of certain forms of organic poisons upon public health has

been established by such a great expenditure of pain and of human life that the considerations of health must over-rule every other question in the selection of a source of water supply.

When considering proposed sources of supply, these questions of the requisite purity of a water should receive the most careful attention. It is easy to define a water which is unquestionably good, and equally easy to define a water which is unquestionably bad. The difficulty of examination and determination lies not in these extremes but in the limiting cases. For perfect safety it might seem a simple precaution to reject any suspicious water, but this cannot always be done. When a water is simply doubtful and when a change involves a large expenditure or when the rejection of a supply compels the adoption of plans for clarification or the adoption of a supply much more expensive to develop, then selection or rejection becomes a serious matter and can be decided only on the best of evidence.

Water supplies for commercial and manufacturing uses must also have certain characteristics. For boiler purposes, waters having a high mineral content produce scale which is a detriment to the boiler and a source of expense in maintenance and as a consequence, causes a loss in efficiency.

For domestic, manufacturing and industrial uses, water supplies that are turbid, polluted or contain a large amount of mineral matter must frequently be adequately treated so that the objectional qualities may be eliminated in order to render them suitable for the use to which they are to be applied.

Suitable water supplies for agricultural uses are not so restricted in character. Certain organic matter, though injurious to animal life, affords plant food and is therefore advantageous instead of detrimental. In the same way, certain normal constituents in solution may afford plant food, but waters highly mineralized, especially those containing large amounts of alkaline matter are harmful and sometimes fatal to plant life.

For navigation and power purposes, the qualities of waters are unimportant, so long as they are not so grossly polluted as to affect the health of navigators and operators or to corrode machinery.

In every case where water is to be utilized as a supply for any purpose, the quantity must be adequate and the supply must be available at the time when it is needed for the purpose in view. If the average supply for the year is equal to the average demand and, as usually obtains, the supply varies greatly from time to time while the demand is

more or less constant, the superabundance of water at one season can supply the deficiency at another period only by the utilization of adequate storage. This involves the questions of evaporation, seepage and, in domestic supplies, the maintenance of an adequate degree of purity.

26. Control of Water.—One of the normal functions of water is its cleansing property, and experience has demonstrated that the utilization of this function is usually the most advantageous method of temporarily disposing of those domestic and manufacturing wastes that can be so transported. Domestic sewage, street washings, spent dye stuffs and other wastes of civilized communities are therefore commonly discharged through sewers to some point of disposal at a distance from their origin and where their presence is less objectionable. If discharged directly into a stream they may materially increase its pollution, render it unfit as a source of public or private water supply and possibly so pollute it as to destroy the fish and convert it into an open sewer highly objectionable to those who live along its banks. With the increase of population it therefore becomes essential to provide methods for the disposal of the wastes of a community that will not be detrimental to others who may occupy lower portions of the drainage area.

In the practice of agriculture, which is essential to the maintenance of a large population, similar conditions arise. The natural sod, the forest covering, and even the undisturbed consolidated earth, normally afford a considerable degree of protection from erosion. When the forest is removed, the sod broken, and the soil cultivated, the conditions become more favorable to erosion; and under certain conditions soil waste rapidly takes place. This occurs most rapidly on steeply inclined hillsides where the runoff acquires a high velocity and consequently a great power of transportation. Where such wastes occur, there is not only a considerable loss of available agricultural land which can never be replaced, but the transported materials render the stream turbid, fill pools and impounding reservoirs, and form bars in stream channels to the serious detriment of water storage and navigation. These conditions are also important and demand consideration and control (see Fig. 9).

The existence of swamps and marshes in the vicinity of centers of population create conditions which require attention. Swamp lands are not only useless for cultivation, but they are unsanitary both because they supply the air over and around them with undue moisture and because they furnish a breeding ground for insects detrimental

to human life and happiness. These lands when properly drained often furnish some of the best agricultural lands, hence their reclamation commonly increases both the public health and the wealth of the community.

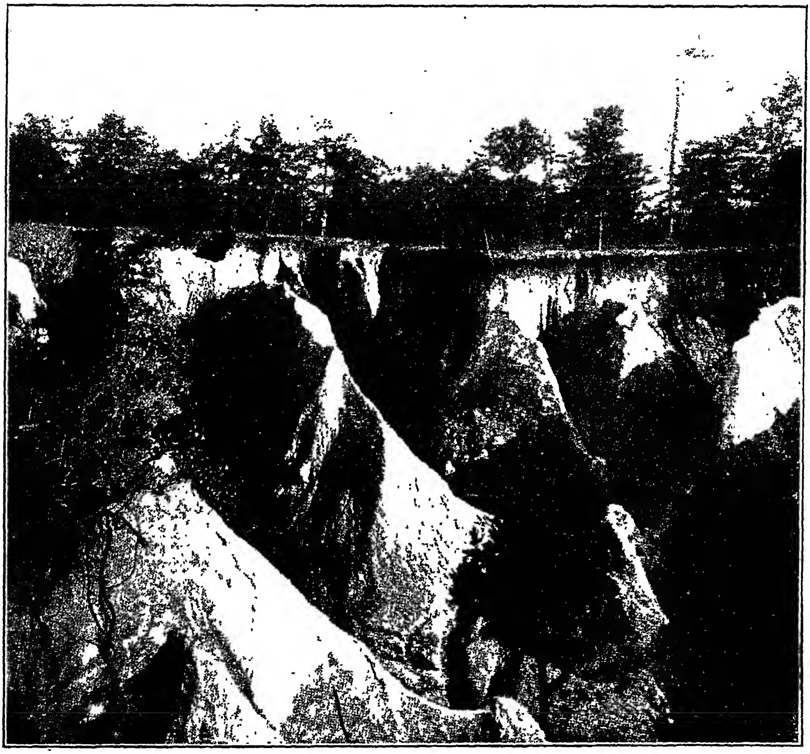

Fig. 9.—Rapid Erosion in Deeply Decomposed Soil Mantle near Marion, N. C.[2]

The bottom lands or flood plains along the rivers and streams of the country are often the direct creation of the streams which occupy the channel to which they are adjacent. Many of these lands are inundated by every considerable flood, while others higher above the stream are covered only by those occasional high floods that may occur at rare intervals of possibly twenty or fifty years or possibly only once in a century or more. Attempts are often made to utilize for agricul-

[2] Denudation and Erosion in the Southern Appalachian Region, by L. C. Glenn. Prof. Paper 72, U. S. G. S.

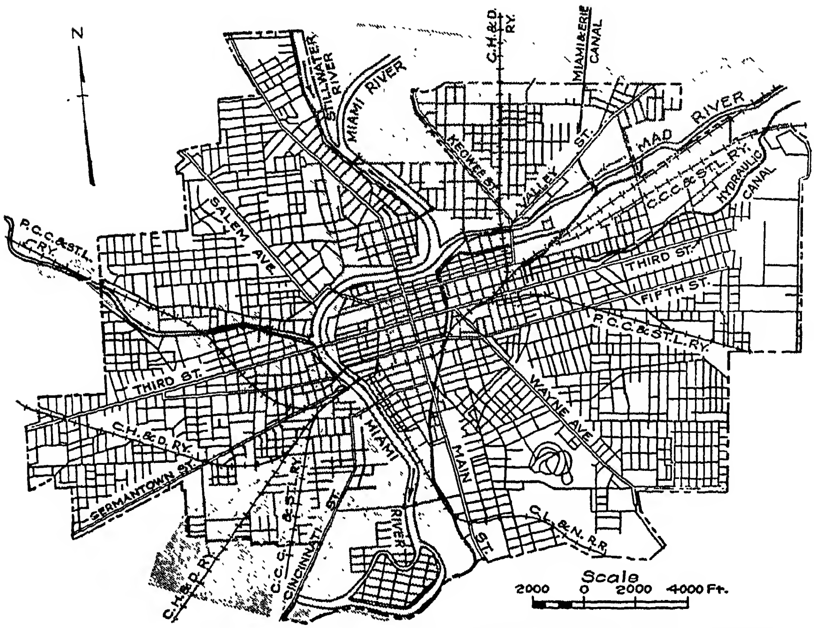

FIG. 10.—Map of Dayton, Ohio. Shaded Portion Shows Area Flooded in March, 1913. Ground Saturated; Rainfall in Four Days about Nine Inches (see page 41).

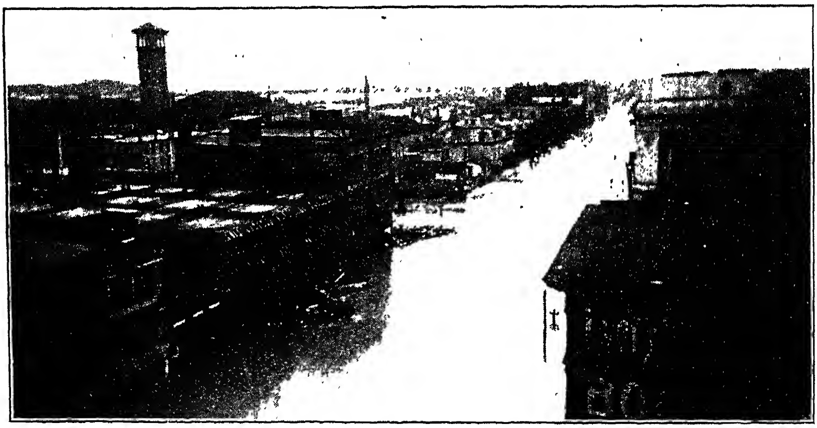

FIG. 11.—Dayton, Ohio. Flood of March, 1913 [3] (see page 41).

[3] From Report of A. E. Morgan, Chief Engineer Miami Conservancy District.

tural purposes lands which are frequently inundated. When these floods occur after crops are planted or before they are harvested as is often the case, considerable losses are entailed and works for the protection of such lands are in frequent demand.

The level land adjacent to streams furnishes desirable building sites, and the absence of floods, save at rare intervals, has in some cases induced the development of communities and industries in locations which are occasionally exposed to serious overflow. To secure valuable lands and to cheapen the construction of bridges, even the natural channel of the stream is often restricted, and occasionally such channels are so limited that when the rare extreme flood does occur, these channel restrictions and structures built in the natural path of the flood, cause congestions which result in great losses of life and property. (see Figs. 10 and 11, page 40).

The protection of communities from such losses, often occasioned by their own folly and short-sighted policy, becomes a matter of the utmost importance.

In a similar manner, and for commercial purposes, many large communities are located on the low lands adjacent to the large bodies of water such as the lakes and oceans. Frequently also the lands bordering these waters are valuable for agricultural purposes. Lands so located, which are perhaps inundated only at high tide, can sometimes be reclaimed by the construction of suitable protective works which must not only hold back the water but be sufficiently substantial to withstand the effects of currents and waves to which they are exposed. Such lands are also occasionally subjected to extreme conditions resulting from extraordinarily high tides and heavy waves which may occur only at rare intervals under unusual storm conditions.

27. **Necessity for the Study of Hydrology.**—It is apparent that in order to meet intelligently the manifold conditions that arise in connection with the utilization of water for the many purposes to which it must be applied, and its control in the interests of human health, happiness and prosperity, the entire subject of its distribution and circulation on and within the earth's surface must be investigated and understood. To utilize or control these waters to the best advantage, the engineer must know the principles that underlie their circulation, the regularity or irregularity of their occurrence, their quantities, qualities and distribution, and the possibilities of retaining, storing, regulating and controlling their flow and their use. The subject is not a simple one for the elements of these problems include the great cosmical laws

which are understood only imperfectly but on which depend the changes and variations of the season. They include the principles of meteorology, the science that treats of atmospheric conditions and changes, also the principles of geology which treats of the past and present conditions of the earth's surface and the causes and results of topographical growth and development. All of these subjects must be considered in their hydrological relations and in connection with the subjects of hydraulics and hydrodynamics, which treat respectively of the laws of flow of water and of its power in motion. To secure the best perspective of this complicated subject, pertinent conditions that obtain must be observed and interpreted in the light of scientific knowledge as at present developed, in order that the various phenomena may be understood and correctly correlated and applied to the solution of the present problems with which the engineer has to deal.

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Detailed reference to the principal publications relating to various special subjects will be found under the special chapter to which the subject matter of the respective publications more especially refer.

CHAPTER III

SOME FUNDAMENTAL THEORIES

28. **Growth and Development.**—Even limited observation of material objects will show that all things are subject to continual changes in both form and condition; that nothing on earth is permanent but that all things are passing through a continuous evolution.

Organic life develops from the seed and passes through youth to maturity, old age and death. A similar transition takes place in the case of inorganic forms and the conditions resulting therefrom. A continual change is apparent, visible in the more stable forms perhaps only through long observations but no less actual when centuries are considered. A careful study furnishes convincing proof that everything is subject to growth and development and to final decay and dissipation. Nature is never stationary but always progressive, and the character of its progress, its trend and destination within the limitations of the life of a man or a nation may be of great importance in considering engineering works of magnitude and of comparative permanency.

Of the origin and conditions of things and of the nature of the ultimate evolution from present conditions, science furnishes no information and speculation can arrive at nothing definite. Science must deal largely with the conditions of the present. It may go back a few ages in the life of the earth by reading from the geological record the conditions that have prevailed in ages comparatively recent, and in the same manner it may forecast the future for a few years, insignificant perhaps in comparison with the limits of eternity but sufficient at least for the practical purposes of mankind.

29. **Past Conditions and Their Evolution.**—At one period in its history the earth was probably at such a temperature that no water existed even in the form of vapor, the temperature being so high that the association of oxygen and hydrogen as aqueous vapor was impossible. With the gradual reduction of temperature, chemical union first became possible, and as the reduction proceeded vapor was formed, condensation took place and the first precipitation occurred. With the high surface temperature of the primitive earth crust, evaporation rapidly followed and circulation was both rapid and violent. the resulting effects on the modification of surface forms being corre-

spondingly great. As soon as the temperature reductions were sufficient to permit of the existence of water in stable liquid form, the depressions of the crust began to fill and the changes from primitive to present forms began.

The present condition of the earth's surface is the result of previous conditions and numerous forces which have been in action since the beginning of time and are still in action.

The intensity of the action and the resulting effects have undoubtedly varied with the prevailing conditions and while the engineer can have but a poor conception of the great changes that have occurred in the past and the forces which have produced them, he can by study and investigation obtain a sufficiently clear idea to enable him to understand the causes of many of the present conditions and the forces which are now acting and which must be utilized or appreciated to bring about a successful outcome of his work.

30. **Fundamental Considerations.**—It is necessary for a proper appreciation of the subject to consider certain fundamental conditions which underlie all problems concerning the earth and the continual changes which are in progress.

Powell has pointed out [1] that the earth is encompassed by three envelopes each active and changeable to a greater or less extent.

First.—The rock envelope or lithosphere.

Second.—The aqueous envelope or hydrosphere.

Third.—The air envelope or atmosphere.

These envelopes are inter-active one on the other and a complete knowledge of one necessitates a practically complete knowledge of the others on account of the mutual relations.

Little is known concerning the great central mass of the earth, for the deepest mine or the deepest borehole has penetrated the outer crust or rock envelope for only a few thousand feet.

The rock envelope consists of masses of rock of various degrees of hardness, porosity and homogeneity arranged in both stratified and unstratified layers and beds, and in heterogeneous piles. The rock masses are physiographically arranged in mountains, hills, valleys, plateaus, plains, and in swamp, lake and ocean beds, all quite clearly defined in outline but projecting into both the air and water envelopes and admitting these envelopes into their structure through caverns, crevasses, cracks and pores.

[1] Physiographic Processes by J. W. Powell.

The water envelope covers more than three-quarters of the earth's surface and hydrographically consists of oceans, seas, lakes, swamps, streams, snow and ice fields, ground waters, aqueous vapors and clouds.

The atmosphere covers the earth and waters to a great depth, and develops in its mass winds, cyclones and tornadoes.

The envelopes are always in motion and always changing but not with the same degree of rapidity. The rock envelope is apparently the most stable; that is, its changes occupy a greater length of time than aqueous and atmospheric changes, but the changes are no less radical and complete. The sea bottom of one age becomes the plains, plateaus or mountain tops of another age; the hills become valleys, and the mountains islands, for the land though apparently stable is only relatively so and is rising or falling, receiving accretion or being eroded and carried to other localities.

The water envelope is less stable and more actively changing: the snow and ice fields melt and with the rainfall form rivers, and the rivers run to the sea; the waters of the land and sea evaporate or vaporize into atmospheric moisture, condense into rain, snow and other forms and in such changes radically affect both the rock and atmospheric envelope.

The atmospheric envelope is still less stable and its changes from calm to storm are more radical and apparently more erratic.

These envelopes are interacting among themselves. Each is affecting the others; each is modifying the activity of the others and may be either reducing or accelerating such activity.

31. **The Atmosphere.**—The earth's atmosphere has most important influences on the evaporation of water, the distribution of aqueous vapor, and its precipitation. While evaporation would take place regardless of the atmosphere, yet the atmosphere being always present modifies and controls the prevailing conditions. The atmosphere extends outward from the surface of the earth with diminishing density for an unknown distance. The sensible height to which it extends is about fifty miles, for although at this distance the density is not sufficient to produce a measurable pressure, yet its presence in an appreciable amount is made manifest by the diffraction of the rays of the setting sun. That the atmosphere extends to a much greater distance than this has been shown by observation of meteors which become luminous on entering the atmosphere.

"At heights greater than about nine miles the temperature remains nearly constant at about —70° Fahr. and is known as the *isothermal*

or *advective* region. The atmosphere of this region appears practically free from water vapor and takes no active part in circulation."[2]

The air is composed of four principal gases which are in mechanical mixture only. These gases in the proportion by volume present in a normal sample of air are:

Nitrogen	78.04 per cent.
Oxygen	20.99 per cent.
Argon	00.94 per cent.
Carbon Dioxide	00.03 per cent.

This analysis is not exact for all cases since the percentage of the various gases varies with the geographical location, elevation and local conditions.

As the elevation increases the nitrogen and oxygen of the atmosphere diminish in quantity and at the highest elevation probably little trace exists of any gas but hydrogen.

The atmosphere besides furnishing the gases necessary for the support of plant and animal life, contributes its offices in other ways to the activities of the earth's inhabitants. It carries bacteria, plant spores and the winged seeds of various large plants; the flight of insects, birds and man is made possible by its presence; sound would be impossible were it not for the presence of the air. By virtue of its circulation over the surface of the earth, it supplies power to drive sailing vessels and furnishes power to wind mills; it transports moisture from the sea and precipitates it over the land; it assists in the weathering of rocks and by its movement produces waves in the sea.

While the composition of the atmosphere is approximately constant at all points on the earth's surface yet on account of the relations of different points of the earth's surface to the sun and on account of the differences in relations of sea and land surfaces, the physical conditions of the atmosphere differ from place to place and from time to time in the very important matter of temperature. The range in the extremes of temperature vary from perhaps—90° to 180° Fahr. and is small compared with the extreme range of temperatures known to science yet it gives rise to the variations from the ever frozen polar regions to the heat of the desert.

32. **Atmospheric Temperatures.**—Atmospheric temperatures, which are important factors in atmospheric circulation and hence in the distribution and occurrence of moisture and precipitation:

First.—Decrease from the equator to the poles.

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2 Climate and Weather, H. N. Dickson, p. 76.

Second.—Decrease with altitude above sea level.

Third.—Increase with the advent of day and decrease at night.

Fourth.—Decrease as the surface of the earth receives the more inclined rays of the sun, due to the revolution of the earth in its solar orbit, and

Fifth.—Vary with the winds, and with the relative humidity.

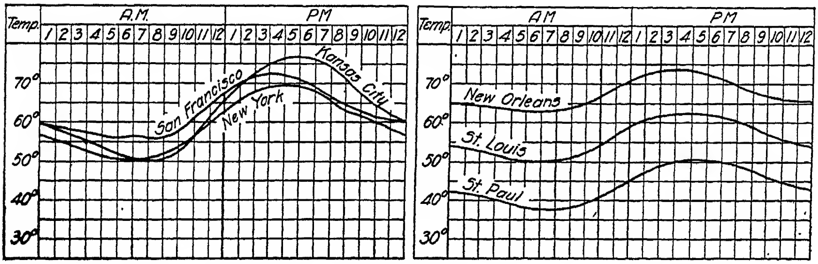

FIG. 12.—Mean Diurnal Changes in Temperature at Various Stations in the United States (see page 48).

The heat changes at the earth's surface are of great importance. Practically all of the heat received at the surface is from the sun. Various rays from the sun received through the earth's atmosphere give rise to various colored light, produce certain chemical effects, and when stopped by opaque objects are converted into heat.

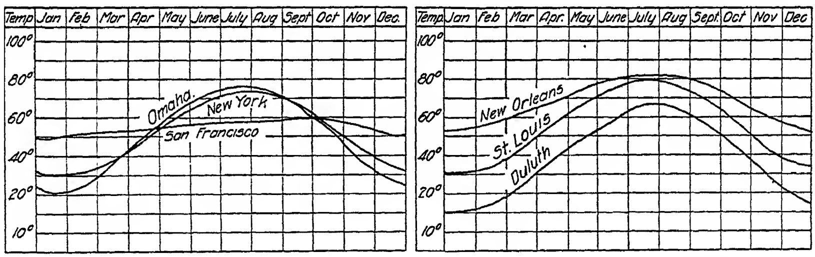

FIG. 13.—Mean Annual Variations in Temperature at Various Stations in the United States (see page 48).

Atmospheric temperatures are the result of the heat received from solar radiation, both directly by absorption of heat from the solar rays, and also indirectly by contact with and radiation from the surface of the earth. While it is generally believed that the earth's interior still remains at a high temperature, the earth's crust is such a poor conductor of heat that this interior heat has very little effect on surface temperatures or surface radiation, and the temperature of the earth's sur-

face and of the atmosphere is therefore controlled largely by solar radiation.

Even in midsummer with the sun at the meridian, its rays reach the earth's surface in polar regions at a considerable inclination, while between the tropics the inclination is comparatively small. The distance of the earth from the sun and the altitude of the sun at the meridian therefore vary least during the year at the equator and most at the poles. In consequence the greatest difference in tem-

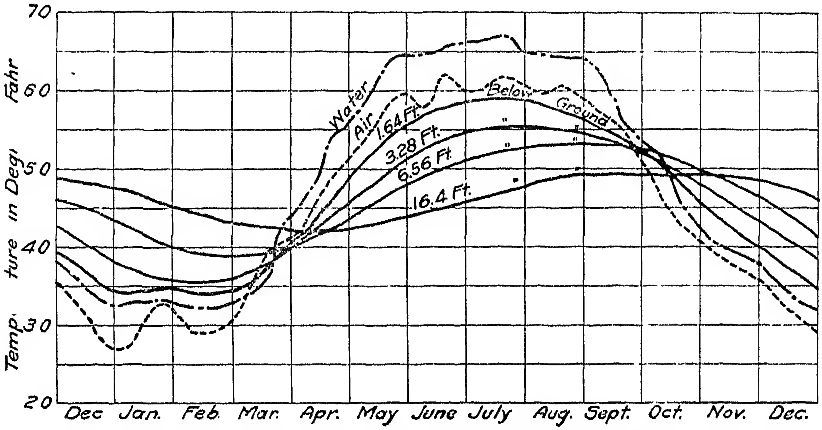

FIG. 14.—Variations in Temperature of Air, Water and Earth at Hamburg, Germany (see page 49).

perature between day and night occurs at the equator and the least at the poles; while the greatest annual variation between winter and summer occurs at the poles and the least at the equator.

The conditions above described give rise to diurnal (see Fig. 12, page 47) and annual (see Fig. 13, page 47) changes in atmospheric and surface temperatures.

Of the incident solar heat, the atmosphere absorbs an average of about 76 per cent, about 50 per cent being absorbed by a cloudless and practically all by clouded atmosphere.[3] Of the solar heat reaching the earth's surface, four times as much is absorbed by the land as by the water surface.

The solar rays falling on soils and rocks are absorbed and converted into heat, the effect or warmth depending on the specific heat of the substance and its conductivity which vary greatly with different deposits. Loose, porous, air filled soils conduct heat slowly, while solid clay soils especially when saturated with water convey heat very rapidly.

[3] See Descriptive Meteorology, W. L. Moore, p. 78.

The latter are therefore readily heated and quickly cooled and are subject to a great range of temperature. The former warm but slowly and retain their heat which during radiation is replenished from the lower strata; hence such soils or substances have a small range of temperature. The immediate surface areas of the earth undergo the greatest seasonal variations in temperature. As the depth below the surface increases, these variations decrease until a constant temperature prevails which is the balance between the average external and the internal temperatures (see Fig. 14, page 48).

Water is diathermanous, and the absorption of solar heat takes place only gradually from the surface to considerable depths. Its specific heat is very high, hence it has the capacity to absorb and give off great quantities of heat. This results in reducing the range of temperature variation over a sea as compared with the land. Sea water also decreases in specific gravity with a rise in temperature which tends to cause the warmer waters always to lie at the surface. In the case of fresh water, however, the temperature of greatest density is 39.1° Fahr.

The snow and ice covering of the higher latitudes obliterates the difference between land and sea. Snow contains a large amount of air and is in consequence a poor conductor of heat; hence the range of temperature is considerable but is limited in its rise to the melting point. In the temperate zone the snows of winter delay the warming of the soil in spring inasmuch as heat is absorbed by the melting of snow and in its evaporation. The greatest seasonal differences of temperature between sea and land occur in intermediate latitudes where the summer heat is intense.

The annual variations in temperatures of the air, of the waters of the River Elbe, and of the earth to a depth of 16.4 feet at Hamburg, Germany, are shown in Fig. 14, page 48.[4]

The surface temperature of the ocean is considerably disturbed and modified by ocean currents but in a general way these temperatures may be stated as follows:

SURFACE TEMPERATURES OF OCEAN (MOORE)

Geographical Location	*Annual Change*	
At Equator	82° 84° Fahr.	2°
At Latitude 35° N. or S.	50° 68° Fahr.	18°
At Latitude 70° N. or S.	35° 45° Fahr.	10°

The net result of the various factors above described is to produce a somewhat irregular distribution of temperatures on the earth's surface.

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4 Ibid, page 91.

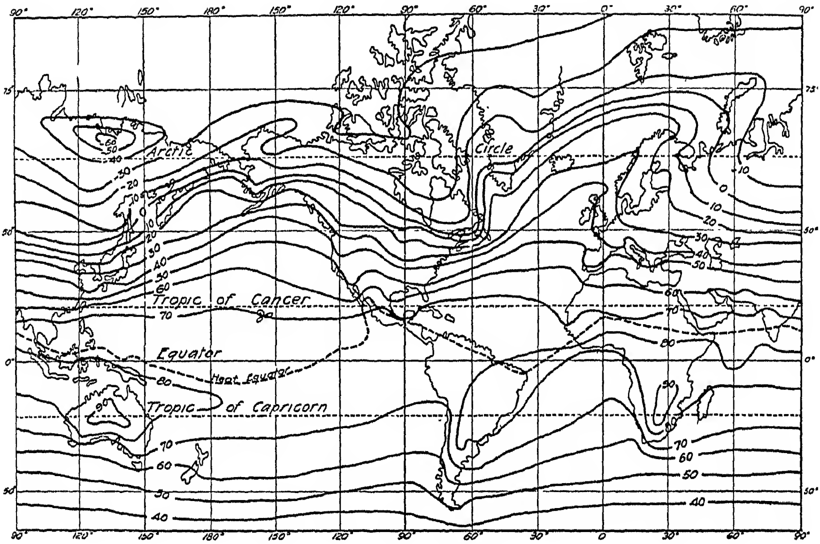

Fig. 15.—January Isotherms (see page 51).

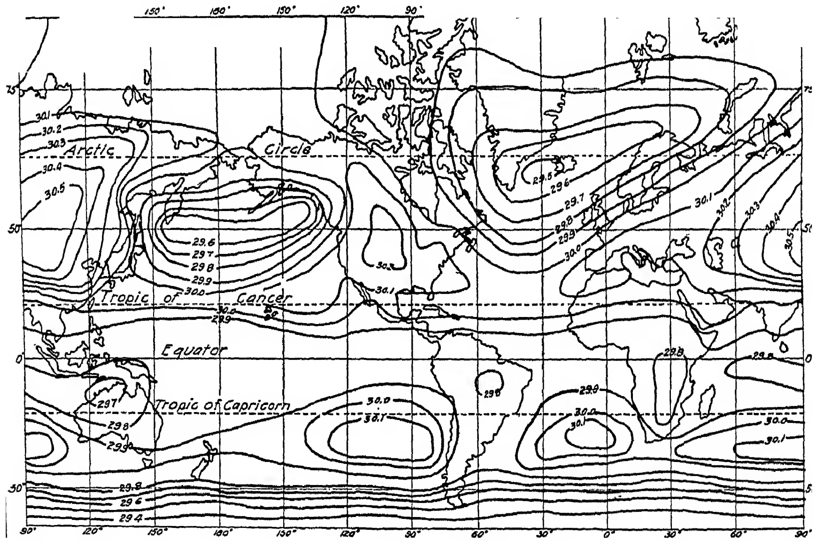

Fig. 16.—January Isobars (see page 51).

This distribution throughout the world for the months of January and July is shown by the isothermal lines on Fig. 15, page 50 and on Fig. 18, page 52, respectively. These lines represent the mean isotherms for the respective months and are modified from year to year by meteorological conditions. They are also modified locally by the passage of storm centers and by anti-cyclonic movements.

33. **Atmospheric Pressures.**—The heat acquired by land and water surfaces is in turn radiated into or through the atmosphere, thus in turn affecting atmospheric temperatures. Atmospheric temperatures and their variations are the direct cause of atmospheric pressures and

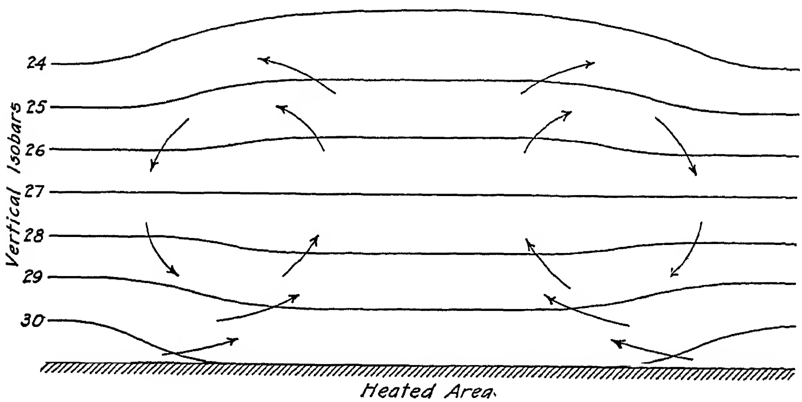

FIG. 17.—Circulation Due to Heated Area.

their variations. *The expansion of the atmosphere by heat causes an overflow from above the heated area, a local or planetary circulation in accordance with the extent of the heated area (see Fig. 17), and a consequent decrease in surface pressure on the heated area.* In consequence of this law and the relative gain and loss of heat by the ocean and land areas at various seasons, the land areas attain their maximum pressure in winter and their minimum pressure in summer, while these conditions are reversed on ocean areas. (See Fig. 16, page 50 and Fig. 19, page 52, in which the lines represent mean atmospheric pressure for the respective months in terms of inches of mercury. These maps should be compared with the maps showing the isothermal lines for the same period which are shown just above them in Figs. 15 and 18 respectively). For the same reason there is a daily fluctuation in the local barometric pressure, the minimum occurring shortly after the maximum heat of the day. (See Fig. 20, page 53 and Fig. 21, page 54.) These fluctuations

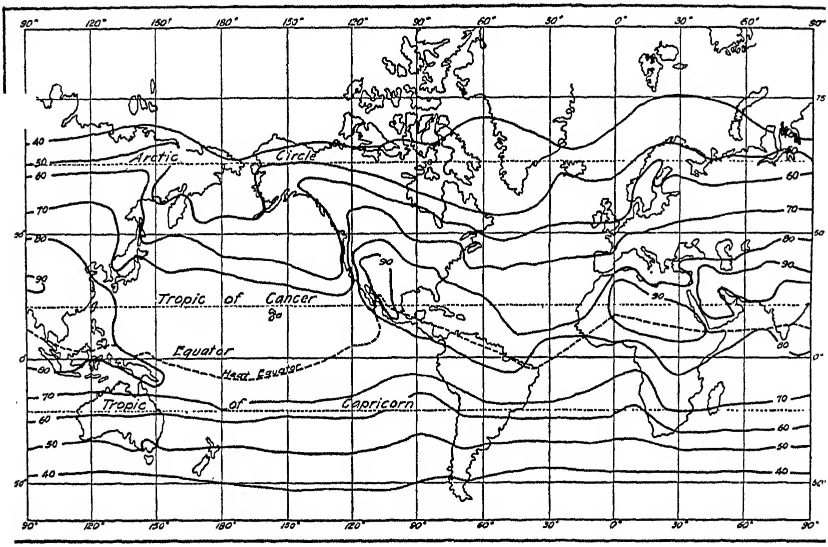

FIG. 18.—July Isotherms.

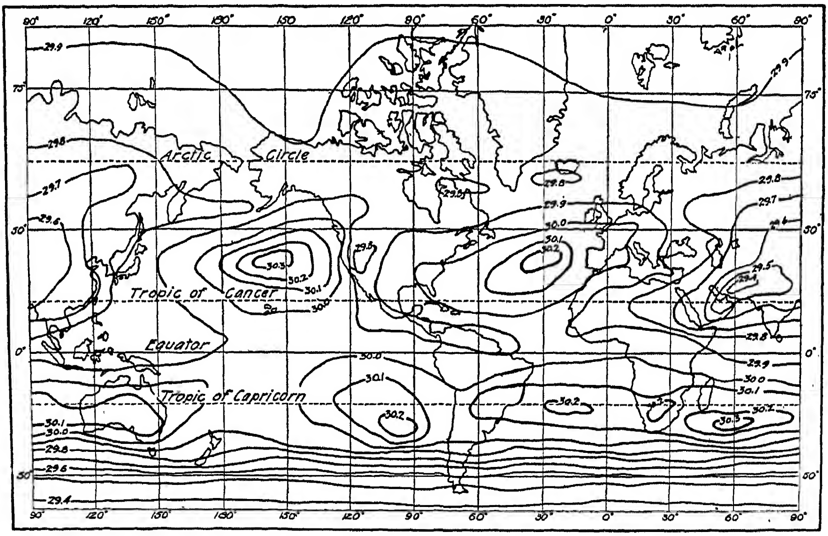

FIG. 19.—July Isobars (see page 51).

are often obscured by non-periodic changes caused by the passage of cyclonic centers or anti-cyclonic centers of disturbance.

Normal atmospheric pressure should be symmetrical and practically the same in all places having a common altitude, for the pressure should

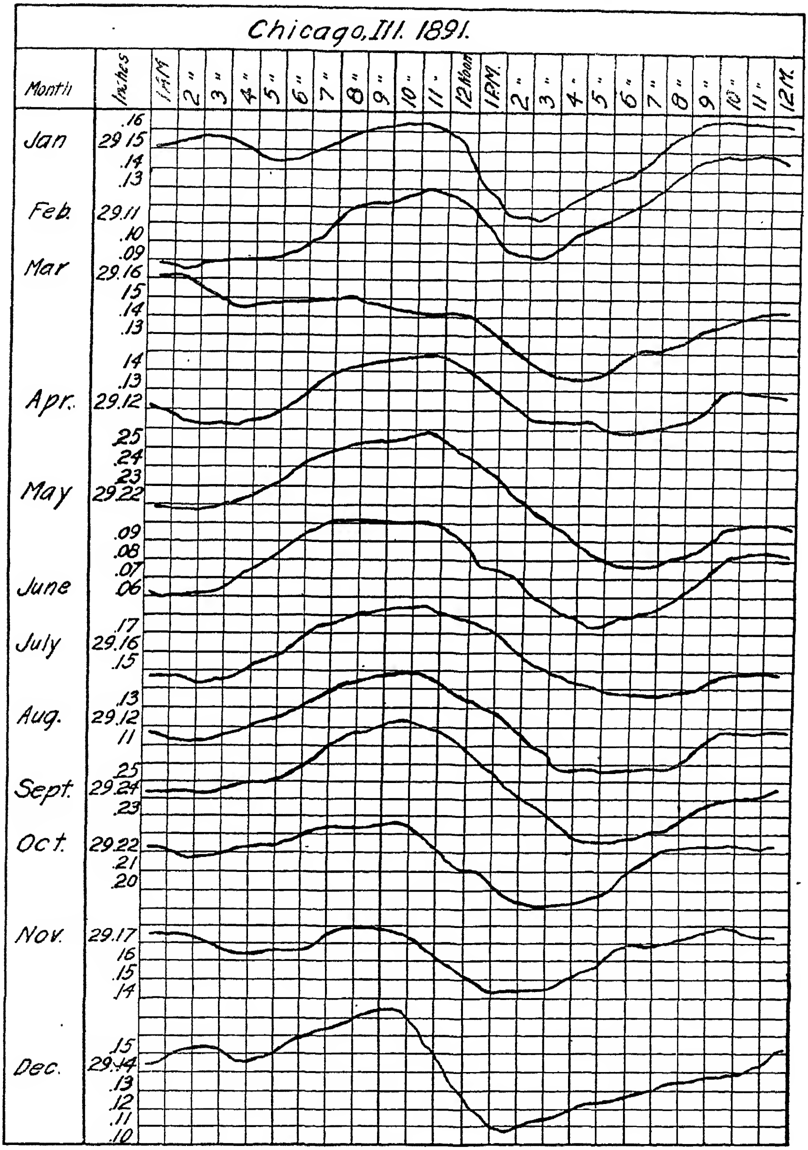

FIG. 20.—Monthly Mean Diurnal Pressure Changes at Chicago.

be equal to the weight of the column of air above the point under consideration, which should be the same for all places of the same height above sea level. The normal atmospheric pressure at sea level is equivalent to the pressure of about 30 inches of mercury or 14.7 pounds per

square inch which value may vary however about one and one-half per cent. with the ordinary changes in atmospheric pressure. Normal atmospheric pressure decreases with the height above sea level, and this decrease may be calculated by the formula

$$(1)\quad \text{Log } b = 1{,}47712 - \frac{H}{64000}$$

in which

b = average barometer reading in inches of mercury.
H = height of station above sea level in feet.

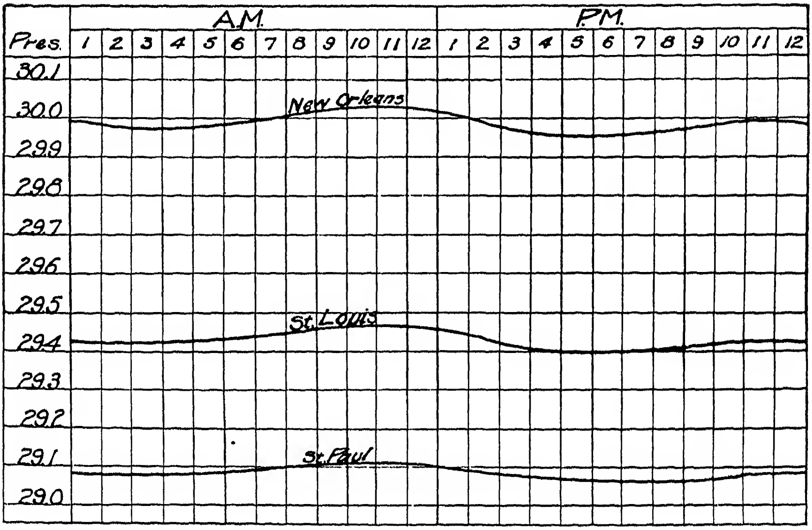

FIG. 21.—Diurnal Pressure Changes at Various Stations (see page 51).

The average pressure per square inch at various elevations above sea level can be determined directly by the following modification of formula (1):

$$(2)\quad \text{Log } P = 1.16801 - \frac{H}{64000}$$

in which

P = the atmospheric pressure per square inch in pounds.
H = elevation of station above sea level in feet.

In Table I are given the average annual barometric readings at various points in the United States as determined by the United States Weather Bureau for 1890 and 1891, with the height of the location of the barometer above sea level and the pressure calculated by formula (1).

TABLE I

Comparison of Observed and Calculated Barometric Heights

Station	Elevation above sea level	Average annual barometer	Calculated barometer	Difference
Key West, Fla.	22	30.02	29.97	—.05
New Orleans	54	29.96	29.94	—.02
Philadelphia	117	29.85	29.87	+.02
Memphis, Tenn.	330	29.66	29.65	—.01
St. Louis	571	29.36	29.38	+.02
Cincinnati	628	29.32	29.33	+.01
Detroit, Mich.	724	29.16	29.23	+.07
Chicago	824	29.06	29.12	+.06
Bismarck, N. Dak.	1,681	28.20	28.24	+.04
Ft. Assinniboine	2,690	27.02	27.21	+.19
Salt Lake	4,348	25.23	25.66	+.43
Santa Fe, N. Mex.	7,026	23.24	23.30	+.06

On account of the disturbing influence of the sun's heat, and the consequent movement of air currents a considerable variation is caused in barometric pressures, these pressures varying with the diurnal rotations and annual revolutions of the earth. The diurnal variation in atmospheric pressures is illustrated by Figures 20, and 21, pages 53 and 54. Fig. 16, page 50 and Fig. 19, page 52 show the sea level isobars for January and July. "From what has been said it will be seen that there is a close relation between temperature and pressure. High temperature expands the volume of the air and causes an overflow at high levels and a decrease in the pressure at the surface. The result is that land areas have maximum pressures in winter and minimum pressures in summer, while the reverse is true of ocean areas. Regions of considerable elevation also have a maximum of pressure in summer for the reason that when the air is cold and dense, a greater percentage of the mass is below this level than is the case when the air is expanded by heat."[5]

34. **The Planetary Circulation.**—Atmospheric circulation is produced by the following causes:

First.—The atmosphere rotates with the earth, of which it forms a part.

Second.—The atmosphere, heated at the tropics, rises and flows toward the poles, as it is cooled, it settles and produces lower counter currents towards the tropics.

Third.—The mixture of aqueous vapor with the atmosphere and the liberation of heat during precipitation, produce and accentuate vertical

[5] *Ibid*, p. 136.

currents which greatly modify the velocities, altitudes and direction of atmospheric currents.

Fourth.—Irregularity in the topographic features of a country causes marked changes in the direction of the lower winds, and produces eddies and irregularities in the lower air currents.

Fifth.—Variations in local temperatures of land or water sometimes modify the local atmospheric currents to a considerable extent.

The very great number of possible relations and combinations among these various causes of atmospheric movements make the winds at lower altitudes seem erratic, while those in the higher altitudes, being free from local influences, are more largely governed by the two first normal and principal causes.

It is evident from what has already been presented that circulation is primarily caused by differences in temperature on the earth's surface, which in turn produce difference in pressure and, consequently, atmospheric movements. The general circulation of the atmosphere is due to the unequal heating of the earth's surface by the rays of the sun. The effect of this is to cause an expansion and consequent ascending of the air in equatorial regions, a poleward flow of the upper atmosphere, a cooling and consequent contraction, descending current and in the lower regions a movement toward the equator. This movement is greatly modified by various causes.

An important principle that has a marked effect upon the atmospheric circulation should here be noted. In a planet revolving on its axis with a certain velocity, the attraction of gravity in the direction of the center of the sphere, combined with the centrifugal force of rotation, will have a tangential component toward the equator at every point except the poles. The component is offset in the planets by the gradual increase in the radius from the poles to the equator which radius, to obviate the development of a component poleward or toward the equator, would have to be reduced if the velocity of rotation decreased and increased if the velocity of rotation should be increased. It follows therefore that any body moving on the surface of the earth under any independent force, and in a direction having a component in the direction of the earth's rotation, will move in space with a velocity in its latitude greater than the earth's rotation, therefore the centrifugal force will increase and a component will develop toward the equator.

In a similar way, any body moving with a westerly component is moving through space slower than the earth in its latitude; its centrifugal force will therefore diminish and a component will be developed

toward the pole. This general principle is known as Ferrel's Law, and may be stated as follows: *Every body moving on the surface of the earth is deflected to the right in the northern hemisphere and to the left in the southern hemisphere because of the earth's rotation.*

At the equator, the earth's surface and the atmosphere in contact with it, which is relatively stationary, have an actual velocity in rotation of about 1,000 miles per hour; the rotative velocity of the surface decreases poleward and becomes zero at the poles. The difference in the relative rotary speed at the equator and poles gives an easterly di-

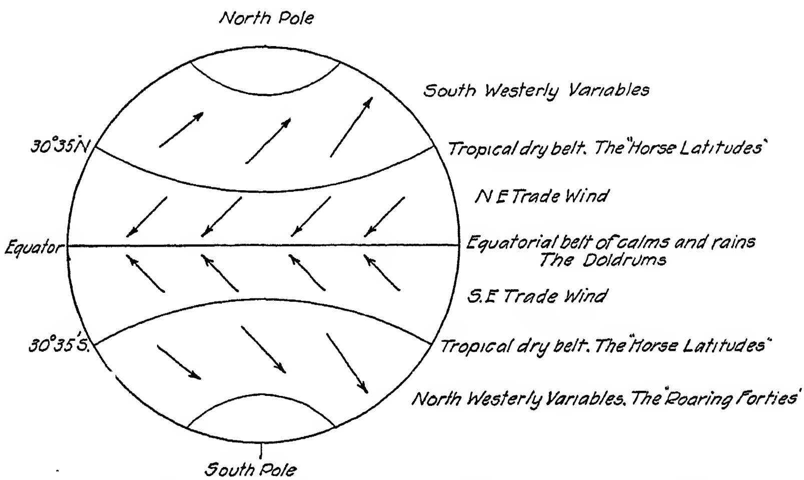

FIG. 22.—Planetary Circulation on a Uniform Planet (see page 58).

rection to the upper poleward flowing warm air currents, and from the same causes the lower return currents are given a westerly direction.

The upper currents, free from the frictional resistance of the earth, acquire high velocities (perhaps 300 miles per hour or more) and a spiral movement in their flow. As the path becomes more nearly parallel to the equator, the centrifugal force due to this high velocity, in the direction of the rotation of the earth, tends to force the air toward the equator in accordance with Ferrel's Law. The return currents from beyond the parallels of 30 degrees are in general deflected westward and hence crowd the air poleward. Thus the effect of both movements is to produce a maximum atmospheric pressure between the parallels of 30 and 40 degrees.

The pressure near the equator is always less both on account of the temperature and the centrifugal force of the earth's rotation. In the region of the poles, the temperature tends to cause an increase in at-

mospheric pressure which is somewhat offset by the deflecting forces above described. Half of the earth's area is included between the parallel of 30 degrees north and 30 degrees south, and in general the ascending currents, strong at the equator, decrease poleward toward the limits of this belt. The descending currents which in general must occupy a similar area, occur in latitudes beyond this belt. The net result of these forces is the distribution of atmospheric pressure shown in Fig. 16, page 50, and Fig. 19, page 52. The low pressure belt at the equator and the high pressure belts between the parallels of 30 and 40 degrees are regions of little horizontal atmospheric movement and of calms.

Fig. 22, page 57 [6] shows the planetary circulation as it might exist on a planet with uniform surface and unmodified by the variation of topographical and temperature relations which actually exist on the earth's surface. As would naturally be assumed, the actual development of this theoretical planetary circulation obtains only when the earth's surface most nearly coincides with the theoretical assumption of uniformity of surface, namely on the oceans, and this circulation is elsewhere modified by the variations in surface conditions.

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[6] See "Climate and Weather," by H. N. Dickson, p. 90.

CHAPTER IV

WINDS AND STORMS

35. **Permanent Winds.**—Permanent winds are found more particularly on the ocean where the planetary circulation is not modified by topographical conditions (see Fig. 23, page 60). As the air descends in the belts of maximum pressures it, of course, enters an area of greater density, and because of the resulting increase in temperature, is dry; hence land areas lying within these belts include nearly all of the permanent desert areas.

The trade winds which originate in these high pressure belts near latitude 30° are among the most constant of the permanent winds. They occupy belts from 12° to 25° of latitude on both sides of the equator, occur at sea some distance west of the continental masses, and blow toward the equator; light at first, they become stronger as they advance and are deflected more and more toward the west. Being fed chiefly from the descending air in the high pressure belt, the trade winds are dry winds in the higher latitudes and therefore in some cases create desert conditions close down toward the equatorial belt. They are permanent and persistent winds, varying in strength but seldom shifting in direction more than a few degrees.

Between the trade wind belts under the meteorological equator is a region of light and irregular winds called the Belt of Calms. The antitrade winds are the winds of the upper atmosphere, opposite in direction to the trade winds.

The prevailing westerlies are the winds of the high latitudes which blow in general from the west. These are of greatest intensity between 40° and 50° south, and blow with greater force than the trade winds. While their movement is in general toward the eastward, there are occasional periods where locally the wind may not blow from the west. The winds of high northern latitudes, while of great force, are variable on account of the interference of cyclonic disturbances due to continental areas. These winds in the United States blow in general with a westerly component more than half of the time.

36. **Pericdic Winds.**—In certain regions, namely, India, East Africa, North Australia and the Lower Mississippi Valley there is an almost

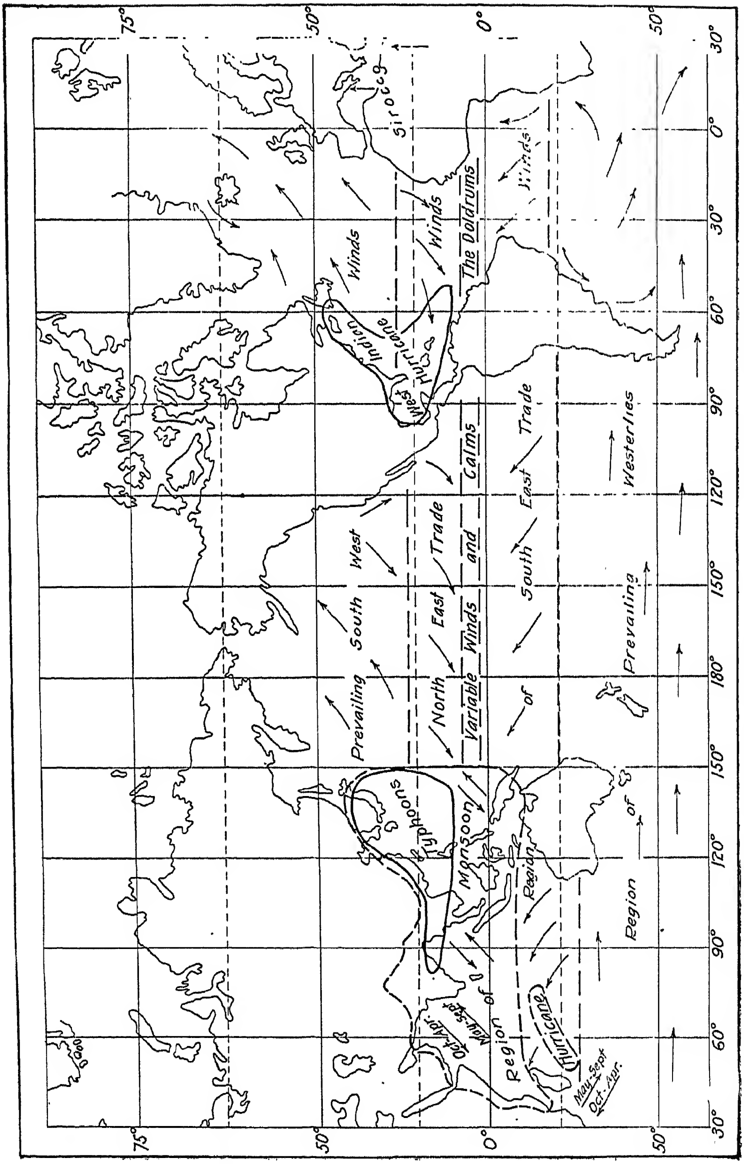

Fig. 23.—Directions of Permanent and Periodic Winds and Regions of the Principal Classes of Winds (see page 59).

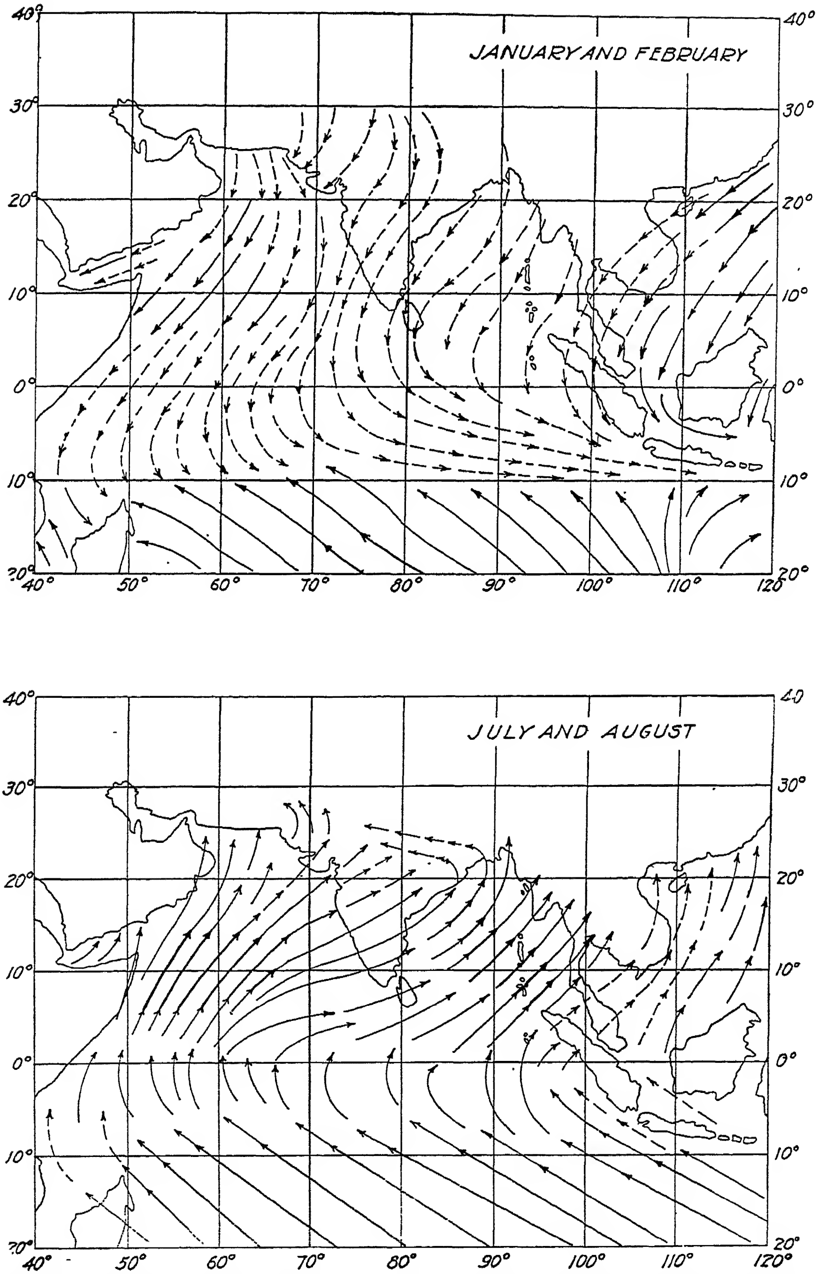

Fig. 24.—Directions of the Monsoons of the Indian Ocean (after Bartholomew) (see page 62).

complete reversal of wind direction between winter and summer; while in Spain, Eastern North America and British Columbia, there is a decided change in wind direction. The most striking example of periodic winds is the monsoon winds of the Indian Ocean (see Figs. 24–A and 24–B, page 61). These monsoon winds are caused by the movement of the colder air to the warmer regions during the seasons of summer and winter, and are usually defined as winds which blow for six months of the year from one direction and for the other six months from the opposite direction. They are, however, greatly influenced by the planetary atmospheric circulations and by topographical features, and the complete reversal of direction seldom takes place.

The land and sea breezes, so named because of their blowing alternately from the land or from the sea, are caused by the radiation and consequent greater heating of the atmosphere over the land by day and over the sea by night. Mountain and valley breezes are similar in nature and are most highly developed where deep valleys open into broad plains.

37. **Non-Periodic or Irregular Winds.**—The normal tendencies of direction of the air current in the planetary circulation in contact with the earth's surface are greatly affected by the larger topographical features of the land which they meet, and by the seasonal temperature changes, and they are often entirely obscured by encountering currents and circulations which are often of a more violent though less extensive character. The planetary circulation is also modified in direction and intensity by the difference in temperature between land and sea, and the temperature irregularities in each, and there is thus produced secondary centers of atmospheric action which, according to their location, character and intensity, are classed as cyclones, hurricanes, typhoons, thunder storms and tornadoes which pass across the country at frequent but irregular intervals. Other non-periodic winds more local in character are still more greatly modified by topographical and geographical features. Such winds are the Foehn, Chinook, Sirocco and Mistral.[1]

38. **Cyclones and Anticyclones.**—Cyclones are the great rotary atmospheric movements which center around low pressure areas. They appear at irregular intervals and progressively pass across the country in a general easterly direction. The greater part of the rainfall, particularly that which takes place within the interior of the continent, is

[1] See Meteorology, by Thomas Russell.

due to winds of this class. These winds are believed to originate as vortices in the great planetary circulation but are modified by a more or less local or regional heating of the earth's surface, which causes a decreased pressure over the area so heated and promotes an inflow from all sides to supply the ascending current, and this vertical circulation is maintained so long as the surrounding atmosphere is in a state of unstable equilibrium. The air in the lower portion, as it flows in from all sides, derives a circular or gyratory motion from the rotation

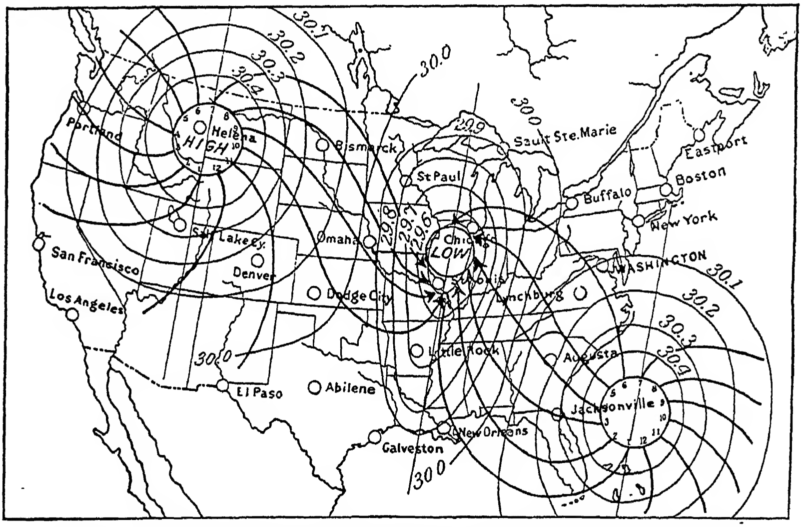

FIG. 25.—Typical Areas of High and Low Pressures[3] (see page 64).

of the earth, similar to the vortex formed in water running out through an orifice in the bottom of a shallow basin.[2] In the northern hemisphere, this circular motion is counter-clockwise, but has the reverse direction in the southern hemisphere. The area within the cyclone, where the barometric pressure is less than that in the surrounding area, is called the "area of low pressure." It is the center of the storm and marks the area of ascending air currents. At and near this center there is a calm area of greater or less extent, depending on the dimensions of the cyclone.

In the region of maximum pressure the air does not descend in a vast uniformly flowing mass but in extremely variable, somewhat lo-

[2] See Ferrel's Law, Sec. 33, p. 57.

[3] Figs. 25 to 30 inclusive are taken from Bulletin No. 20, U. S. Weather Bureau on "Storms, Storm Tracks and Weather Forecasting."

calized descending currents, some of them of strong intensities and some weak. The stronger of these movements, which occur around the outer areas of maximum pressure, strike the earth and because of the friction of the earth surface and of the effect of the earth's rotation are deflected to form eddies in the atmosphere of high pressure called anti-cyclones. The atmospheric movements due to the pressure variations are relatively light and the consequent anticyclonic circulation is slow. The result is that such systems do not endure for any

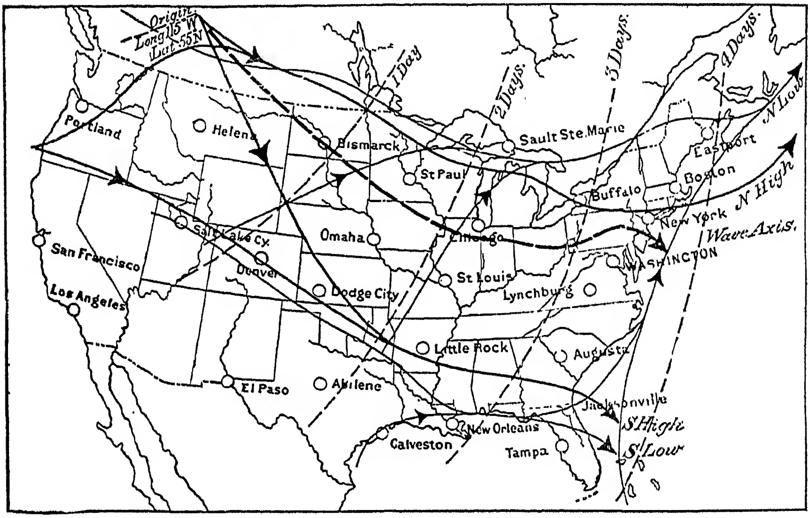

FIG. 26.—General Paths of Atmospheric Pressure Transitions (see page 65).

considerable period but are constantly being dissipated and reconstructed. After their formation they break away from the main areas of maximum pressure and are carried eastward with the general eastward drift of the atmosphere and in their translation become an active factor of variable winds.

39. **The Translation of Storm Centers.**—On every weather map are shown areas of high and low pressure produced by conditions that have already been discussed. The low pressure centers are called the storm or cyclone centers; the high pressure centers are called anticyclone centers, and the winds blow around these centers in the general direction of the hands of a clock but less distinct than in the cyclone (see Fig. 25, page 63). Inside the area covered by the closed isobars of the cyclone, the circulation is upward as well as counterclockwise, while on the area covered by the closed isobars of the anti-

cyclone, the atmospheric movement is downward, bringing cold air from high altitudes. Between these centers is an atmospheric pressure gradient of greater or less magnitude, which causes the air to flow from the high areas to the low areas with an intensity depending on the difference in pressure between these two centers of atmospheric action.

In addition to the atmospheric movement, there is also a movement of these centers on more or less definite paths across the country from west to east. The anticyclones or high centers enter the country dur-

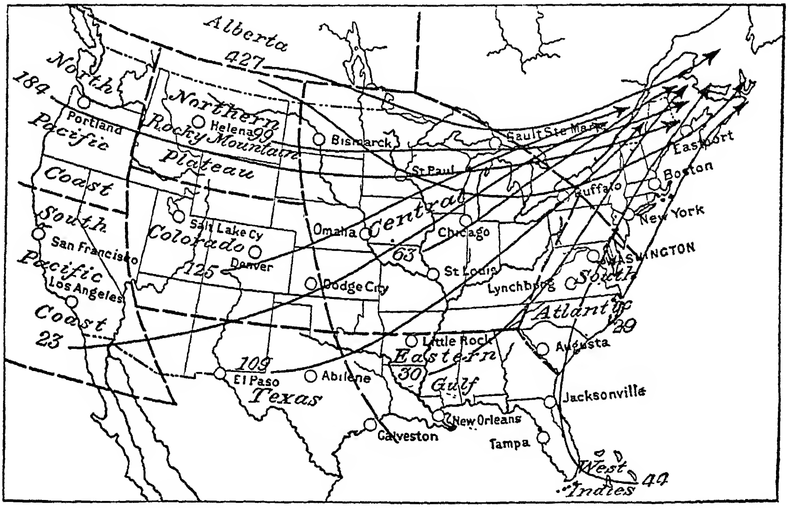

Fig. 27.—Divisions of the United States for the Study of Storm Movement.[3]

ing the winter in general from the northwest. In the summer months the high areas enter the United States from the Pacific and pass southeasterly to Florida or, after entering the country northerly along the Columbia River, they follow easterly to the Gulf of St. Lawrence. From October to March, many areas of high pressure enter the States near the one hundred and fifteenth meridian and either follow along the mountain slope to the southern route or turn abruptly eastward over the lakes to the New England States. The general routes described are shown in Fig. 26, page 64. Storm centers or centers of low area are of more general and local origin. The United States Weather Bureau has adopted nine districts in its study of the local origin of cyclonic storms, and Fig. 27, page 65, shows these districts, the number of storms which were first observed therein and the gen-

eral direction or path of translation of the storms that formed in each district during the ten years' time from 1884 to 1893, inclusive.

40. **Storm Movements.**[4]— The points at which storms originate and their paths, as previously indicated, vary with the seasons. The origin and paths of storm centers, with the number of storms that originated in each district for each month of the year during the ten-year period from 1884 to 1893, inclusive, are shown by Figs. 28, 29, 30, pages 67, 68 and 69. The actual daily barometric conditions which obtained during the passage of certain storm centers for the period of March 20–23, 1913, are shown on the four diagrams of Fig. 31, page 70. These storms originated in the northern Pacific district, passed southeasterly through Colorado, thence northeasterly over the Great Lake region, leaving the country from the extreme northeast. The storm, which was centered over Lake Michigan on March 20, lost its force during the following twenty-four hours and was dissipated. The storm center, which was centered over the southwestern plateau region on the 20th, developed rapidly in intensity and moved northeastward across the Great Plain and was centered on the 21st over the Great Lakes. It was accompanied by strong shifting gales and widespread precipitation, and was followed by a cold wave of unusual severity for March. On March 22, this storm had reached the mouth of the St. Lawrence, but rain was still falling in the Eastern States. On March 23 a third widespread storm had moved forward from Nevada to Colorado and was moving toward the Great Lake region with increasing intensity. The above conditions were those which preceded the heavy rains of March 23–27, 1913, which produced abnormal floods in the Ohio Valley and the northeastern United States, and the further progress of this storm is illustrated by the four maps shown in Fig. 146.

41. **Local Wind Movements.**—As shown by Fig. 23, page 60, the United States is in the belt of prevailing southwesterly winds, and the general drift of the atmosphere is toward the northeast, as shown by Figs. 27 to 30 inclusive. The prevailing winds of any locality may however vary greatly from this general direction, and the passage of storm centers will in each case give rise to radical variations in the local wind direction for the reasons described in Section 38.

Local winds are greatly modified by local topographic conditions and the relative heating of land and water surfaces; they also increase in

[4] See Bulletin No. 20, U. S. Weather Bureau, "Storms, Storm Tracks, and Weather Forecasting."

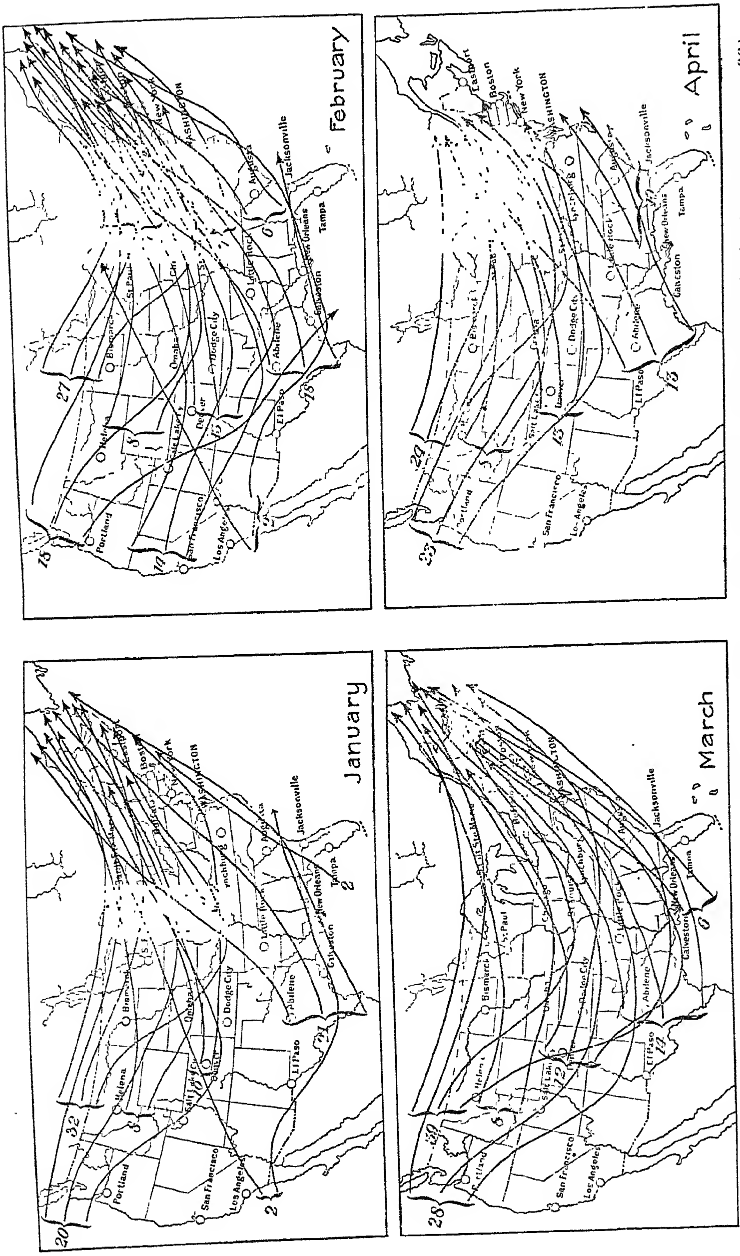

Fig. 28.—Origin, Paths and Numbers of Storms occurring each month from 1884 to 1893, inclusive[3] (see page 66).

Fig. 29.—Origin, Paths and Numbers of Storms occurring each month from 1884 to 1893, inclusive[3] (see page 66).

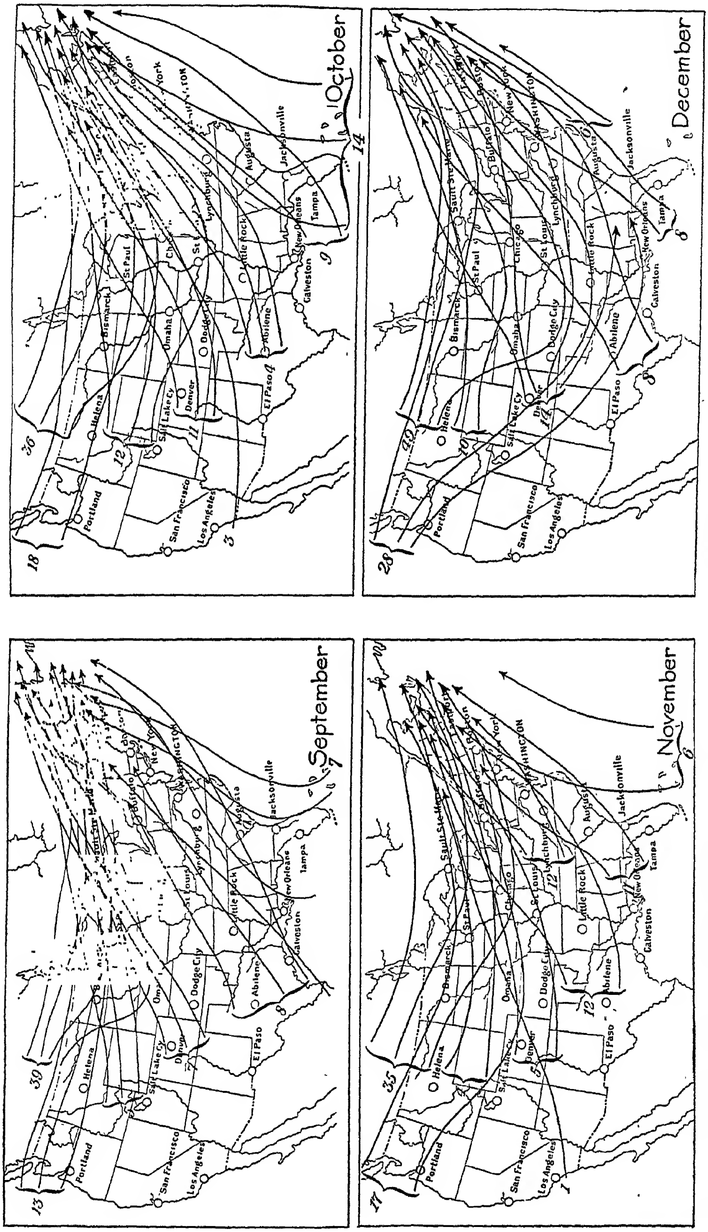

Fig. 30.—Origin, Paths and Numbers of Storms occurring each Month from 1884 to 1893, inclusive (see page 66).

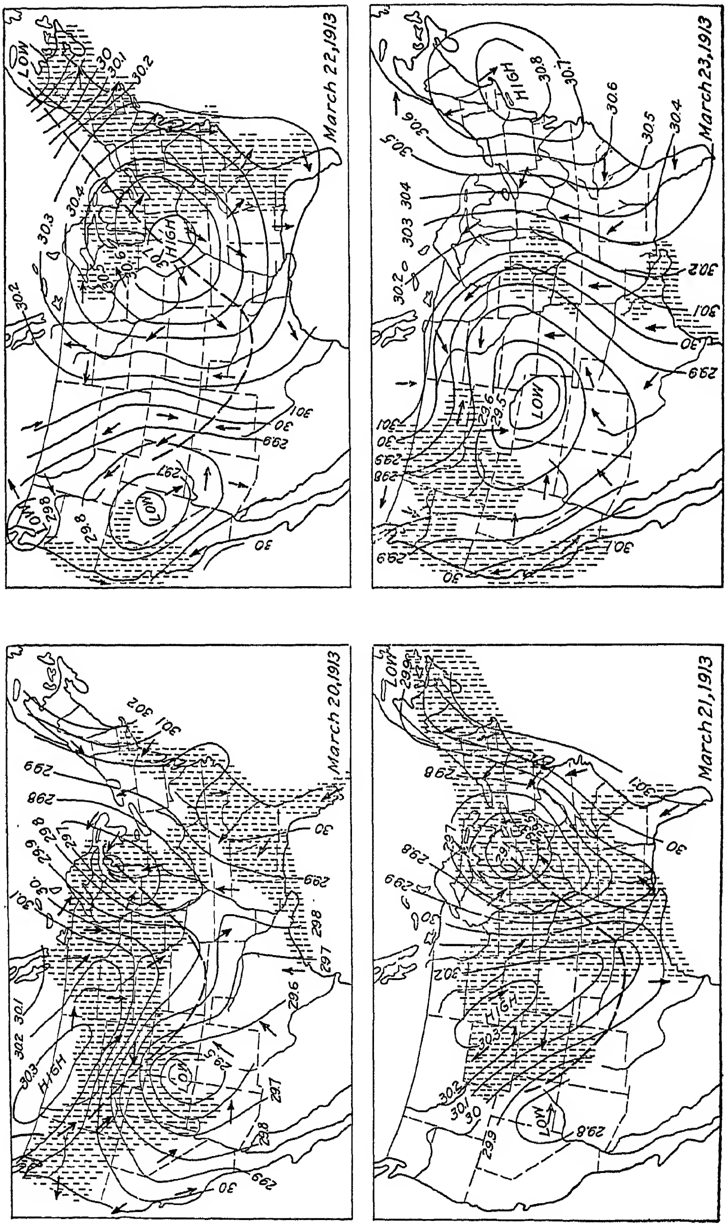

Fig. 31.—Daily weather conditions during passage of the Storm of March 20 to 23, 1913 (see page 66).

intensity with the elevation above the ground surface and near the ground surface with the daily advent of the sun's heat (see Fig. 32, page 71). At stations of high elevations and at all high altitudes the change in the velocity of the wind with the advent of day is reversed from that at stations of low elevation, and the velocities of the wind at night exceed those of the day. (See Fig. 33, page 72). The increase in the wind's velocity with the height above the earth's surface

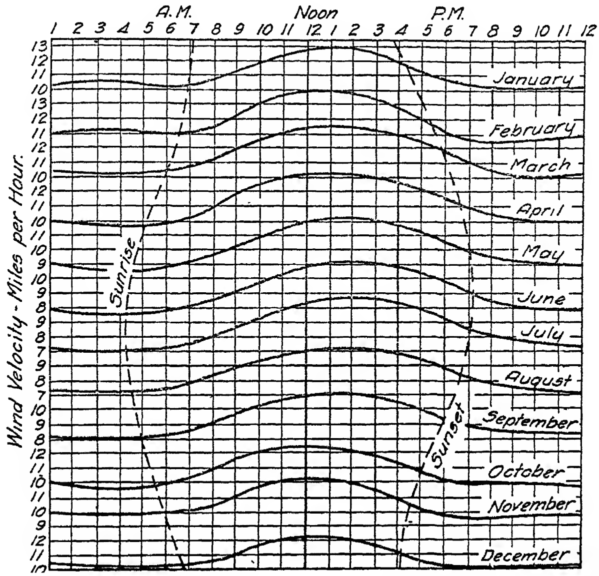

Fig. 32.—Diurnal Variation of the Wind near the Earth's Surface, Atlantic City, N. J.[5]

is less where the station is located near level water or prairie surface and greatest near broken and forested portions of the country.

The average hourly velocity of the winds in various parts of the United States, estimated for elevation of 100 feet above the ground, is shown in Fig. 34, page 72, and the diurnal march of the wind velocities near the earth's surface at both low and high altitudes is shown by Figs. 32 and 33.

While the direction of the local winds varies from day to day and even from hour to hour, due to the passage of storm centers, certain

[5] Figs. 32 to 36 inclusive are taken from the Year Book, Department of Agriculture, 1911. See article on The Winds of the United States and their Economic Uses, by P. C. Day, p. 337.

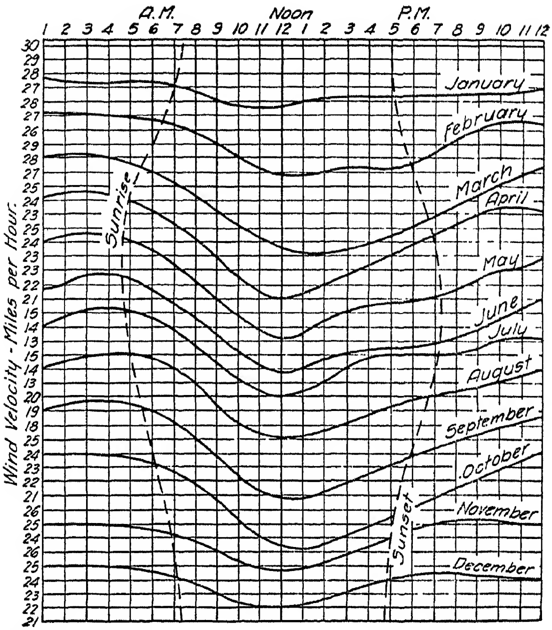

Fig. 33.—Diurnal Variation of the Wind at High Elevation. Pike's Peak, Colorado (see page 71).

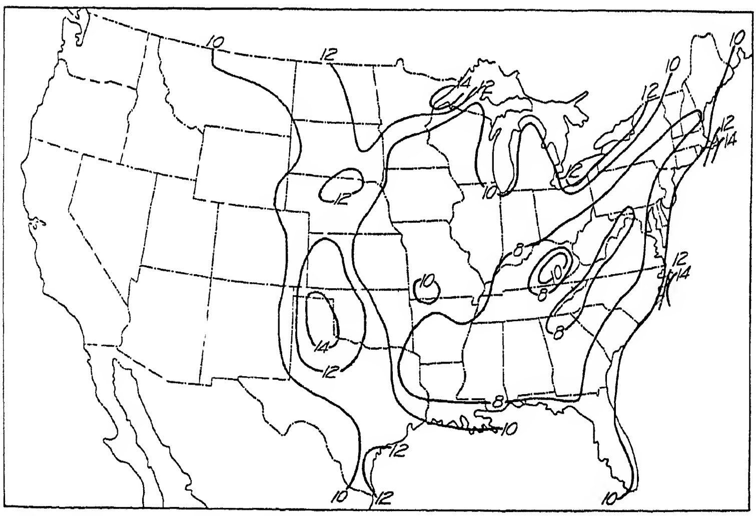

Fig. 34.—Average Hourly Velocity of Wind Estimated for Elevation of 100 feet above Surface[5] (see page 71).

prevailing directions are established by the continuous observation of the Weather Bureau for each locality. The prevailing direction of the local winds of the United States for January and July, respectively is shown in Figs. 35 and 36, page 74. From these maps the various monsoon effects of changes in temperature of the land and sea, due to the season, are well illustrated by the changes in the Eastern States from the prevailing northwesterly winds of winter to the prevailing southwesterly winds of summer.

Table 2 gives the average number of storms originating in each district (see Fig. 27, page 65) annually during the period from 1883 to 1894.

TABLE 2.

Number of Storms Originating in Each District During the Years 1883–1894

District	Average Annual Number of Storms
Northern Pacific	18.4
Southern Pacific	2.3
Northern Rocky Mountain	9.9
Alberta	42.7
Colorado	12.5
Texas	10.9
Central	6.3
East Gulf	3.0
South Atlantic	2.9
West Indies	4.4
Average Number of Storms per Year	113.3

42. **Tornadoes.**—The tornado is more liable to occur in certain parts of the United States than in any other portion of the world (see Fig. 37, page 75). These are storms of the smaller extent and of the most violent type, and in proportion to their size are the most disastrous. They are limited in extent to a width of from fifty feet to about a quarter of a mile and their path seldom exceeds fifty miles in length, whereas the great cyclonic storms which are continually passing across the country are often a thousand miles or more in diameter and their paths can frequently be traced from the Pacific to the Atlantic Ocean. The tornado may occur in any month of the year, but is more common during the period from March 15 to June 15.[6] They occur during the hottest portions of the day and are always associated with violent

[6] Moore's Descriptive Meteorology, pages, 237, 238.

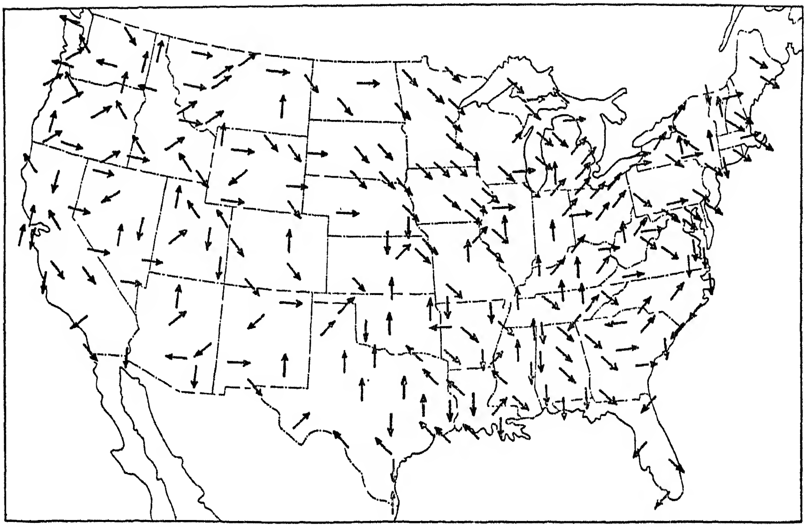

Fig. 35.—Prevailing Direction of the Surface Winds of the United States in January[5] (see page 73).

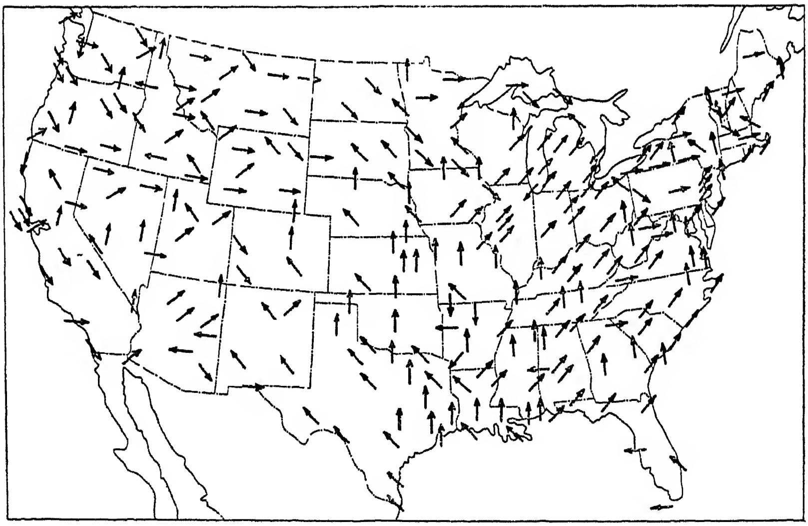

Fig. 36.—Prevailing Direction of the Surface Winds of the United States in July[5] (see page 73).

thunder storms, heavy precipitation and usually with hail. Tornadoes usually form in the southeast quadrant of low pressure cyclonic storms during conditions of great humidity and after a morning temperature of 60° to 70°. They are believed to be the result of rapid local heating of the lower atmosphere, accentuated by southerly winds which create unstable conditions, most frequently resulting in the establishment of somewhat local circulation and consequent thunder storms; but occa-

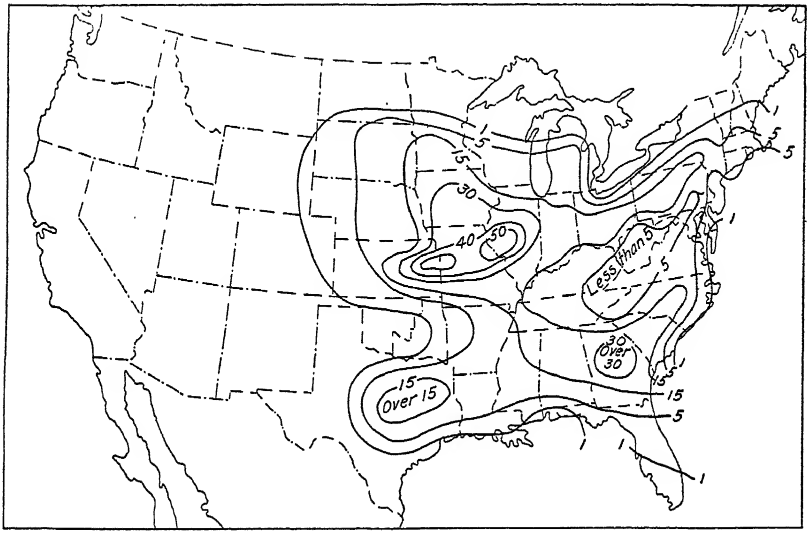

Fig. 37.—Geographical Distribution of all Recorded Tornadoes in the United States from 1794 to 1881 (after Greely—*American Weather*).

sionally there is created a limited vertical whirl which develops the great vortical energy of the tornado.

Before the formation of the funnel cloud, which is characteristic of the tornado, the clouds have a greenish black appearance and appear to rush together with a great violence. The black funnel then appears, drops lower until it reaches the ground surface, when it enlarges somewhat, rises and sways from side to side and sometimes jumps a space and strikes the ground farther on. The destructive effect of the tornado seems to be occasioned both by the heavy wind pressure and the high vacuum which obtains at the storm center and which frequently causes walls to fall outward and buildings to explode, apparently from the outward pressure of the air within. While the conditions favorable to the formation of tornadoes may be foretold, it is not possible

with the present knowledge to forewarn the communities in the exact location where tornadoes may occur without falsely alarming many towns within the district which will be entirely free from such visits. In general, the country 300 miles southeast from the main cyclonic center is in the region of greatest danger.[7]

43. **Hurricanes and Typhoons.**—Hurricanes and typhoons are more limited and more violent cyclonic disturbances than the normal cyclone

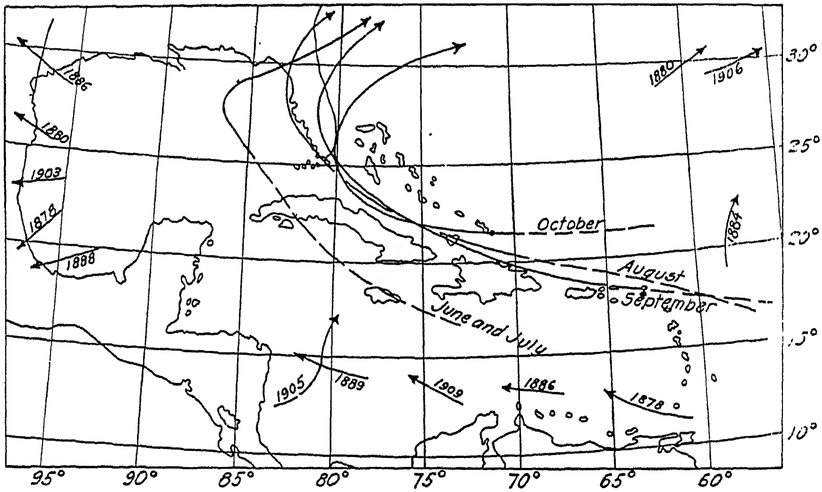

Fig. 38.—Mean Paths of West Indian Hurricanes during different Months 1876 to 1911. Short arrows indicate tracks of greatest deviation from the mean, the numbers are the year of occurrence (after Garriott). (see page 78.)

previously considered and result from a more perfect system of vortices in the atmosphere. The tornado and water spout are of the same character and differ only in more limited dimensions and more intense action. Apparently the deflecting force, due to the earth's rotation, is essential to the formation of the vortex motion which gives rise to cyclones and tornadoes, for no such storms occur in the equatorial belt, although convectional action is there most powerful.

The tropical hurricanes and typhoons, which occur in considerable numbers along the polar margin of the equatorial belt, are generated at the time this belt has migrated farthest from the geographic equator. These storms do not occur far out in the open sea, as the powerful

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7 Milham's Meteorology, page 236.

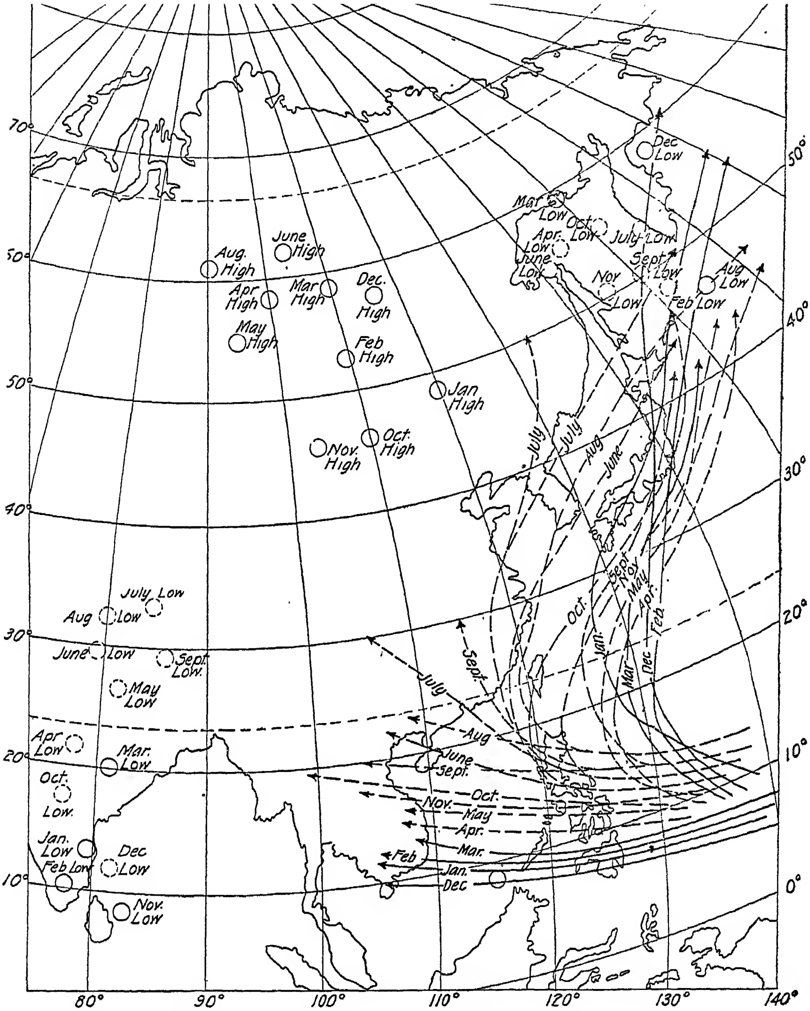


FIG. 39.—Mean Tracks of East Indian Typhoons [8] (see page 78).

trade winds prevent an invasion of their territory, except near the land where the trade winds are weakened by temperature and topographic causes. The origin of hurricanes is probably due to the planetary circulation, modified by the rapid heating of the lower atmosphere, which rises and is replaced by a more dense stratum from above. This, under

[8] Figs. 39 to 41 inclusive are taken from Cyclones of the Far East by Rev. José Algué.

the proper conditions, causes an intense local circulation which creates secondary vortices of the tornado type. In the tropics these follow the general westerly motion of the trades, traveling along the margin of the belt in which they originate, until a weak condition in the west wind zone allows their entry into the regions of western variables.

Such storms are exemplified by the West Indian Hurricanes (see Fig. 38, page 76), and the East Indian Typhoons (see Fig. 39, page 77), which occur chiefly in August and September. In the southern

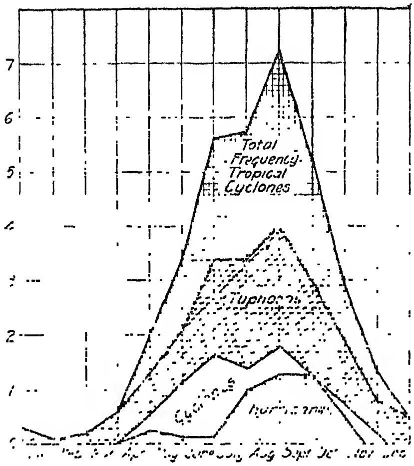


Fig. 40.—Mean Monthly Frequency of Tropical Storms.[8]

Atlantic such storms are unknown and they are rare in the southern Pacific.

In the northern Indian Ocean, on account of its relation to the land, the planetary system of circulation is greatly modified, but cyclones similar in type to the typhoons frequently take place in the Bay of Bengal. In the South Indian Ocean, hurricanes of similar origin are generated in March and April east of the Island of Madagascar. The mean monthly frequency of tropical storms is shown in Fig. 40, and the annual occurrence for each year from 1876 to 1910 is shown by Fig. 41, page 79.

The hurricanes are of greatest interest to the hydraulic engineer on account of their influence on rainfall and on harbor and land protection in the areas in which they occur.

44. **Hurricane Movements.**—In Fig. 38, page 76, are shown the mean paths of West Indian hurricanes during different months from

1876 to 1911. On this map the short arrows represent tracks of storms of greatest deviation from the mean and for the year indicated. West Indian hurricanes are the most severe of any general storms that visit the United States and occasionally, on account of the tremendous winds, the heavy precipitation and the high tides and waves which accompany their advent into the country, cause great loss of life and property.

On the night of September 8, 1900, one of these storms of tremendous force reached the Texas coast near the City of Galveston and

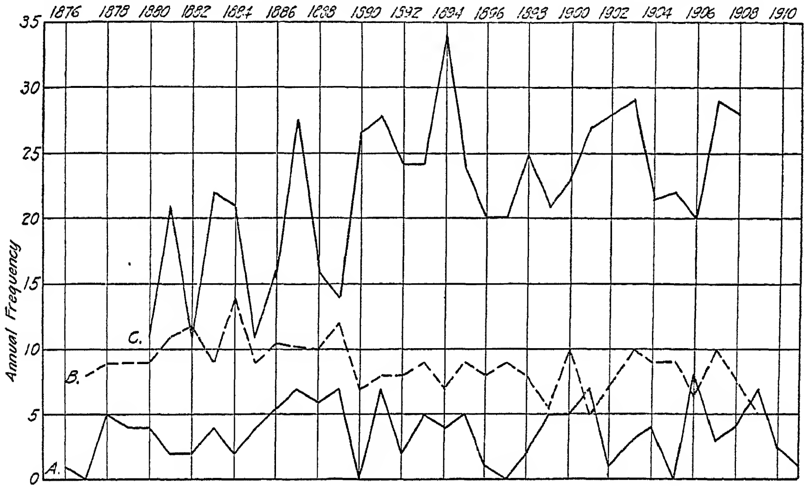
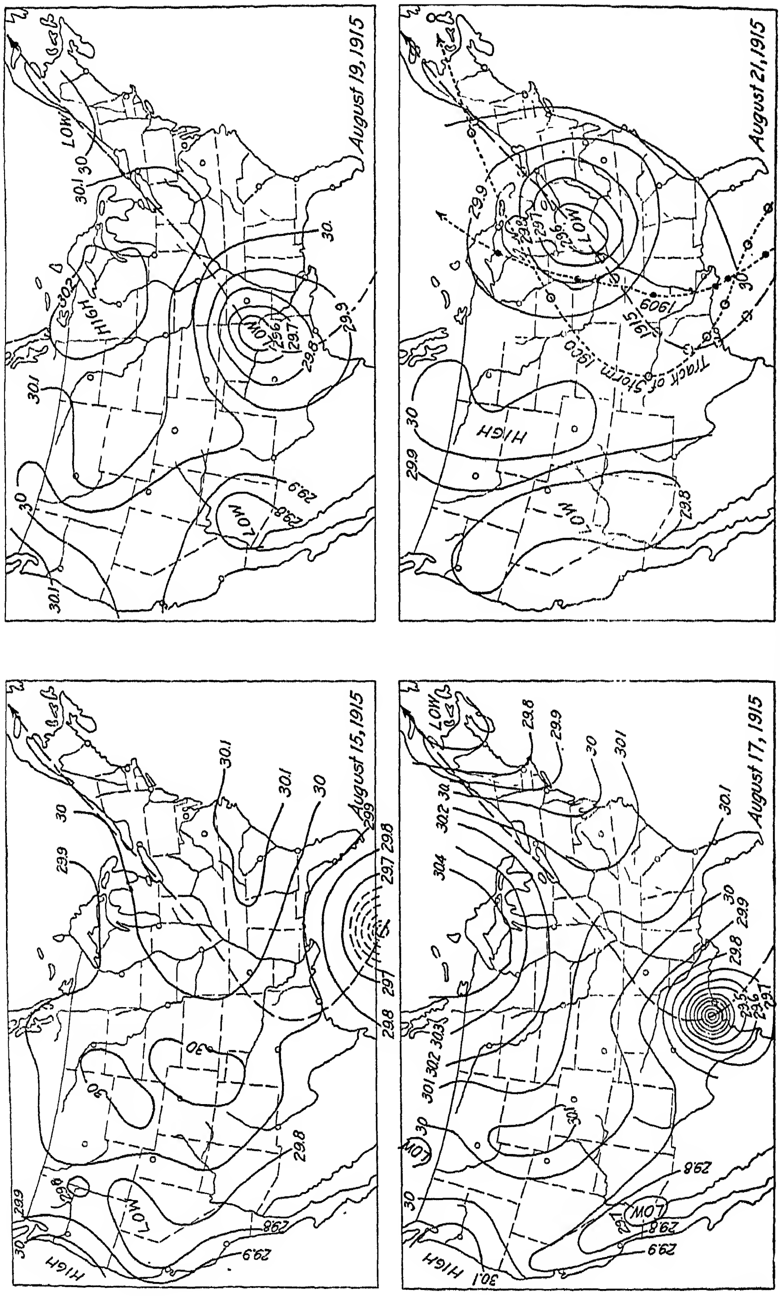


Fig. 41.—Annual Frequency of Tropical Storms: A—West Indian Hurricane. B—Cyclones of Bay of Bengal. C—Typhoons of Western Pacific[3] (see page 78).

caused a loss of over 6,000 lives and of about $30,000,000 in property in the City of Galveston alone. About fifteen years later, on August 17, 1915, a similar storm visited the same locality but with less serious results, largely on account of the precautions which had been taken after the tragedy of 1900 and the warning of the United States Weather Bureau. The loss in this storm, however, amounted to about 275 lives and probably more than $5,000,000 in property. In the interval of fifteen years between these two great storms no severe hurricane visited the Texas coast, except one that passed south of Galveston on July 21, 1909, which caused severe northerly gales and some consequent damages to structures along the shores near Galveston. As the tides were low no lives were lost. The path of the storm of 1915



P Hurricanes of the Gulf Coast.

and the barometric conditions which prevailed throughout the United States for the period August 15–21 are shown in Fig. 42, page 80. Figure 43, shows the air pressure changes at Galveston and Houston, Texas, during this storm. On the map for August 21st are also shown the path of the September, 1900, hurricane and the path of the hurricane of September, 1909, which produced high water conditions near the mouth of the Mississippi River and caused a loss of about 350 lives and a loss of approximately $5,000,000. A similar hurricane also

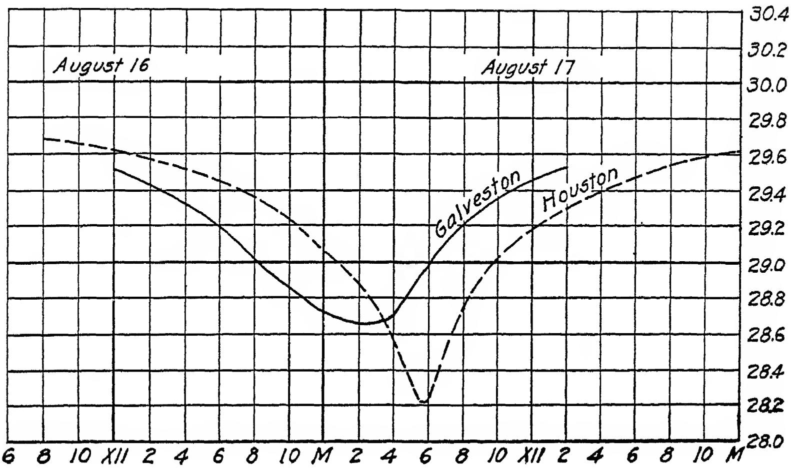


Fig. 43.—Barometric Pressures in Inches at Galveston and Houston during Hurricane of August, 1915.[9]

visited the region of New Orleans on September 29, 1915, and occasioned a somewhat similar loss of life and property.

45. **Cold Waves.**—From the best available data it appears that the lowest temperatures in the Northern Hemisphere are found, not at the north pole, but in a belt that crosses the Continents between latitude 50° and 70° north, and that the lowest known temperature, —90.4°, was experienced in Siberia in latitude 67° 5′ north. This cold belt, which lies next to the Arctic region on the south, is broken where it crosses the water surfaces of Behring Straits and the seas east of Greenland, and is also modified by the influence of the eastern atmospheric drift from the seas over northern Europe and over the western region of the American Continent.

The principal track of high barometric centers in North America

[9] Monthly Weather Review, August, 1915.

lies south of the 50th parallel and their passage disturbs the North American cold belt and draws southward masses of cold air that constitute the cold waves of the United States. These movements sometimes reduce temperatures to —40° or even —60° in the west part of the extreme northern portion of the Central United States, with a minimum of—63.1° at Popular River, Montana[10] (see Fig. 44). The passage of these high areas frequently draws cold air far to the southward, and occasionally during a long term of years temperatures

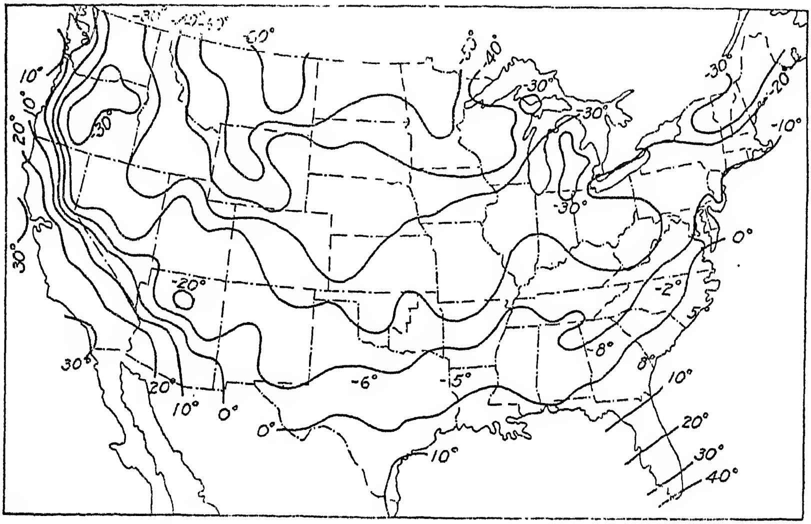


Fig. 44.—Minimum Temperatures in the United States.[10]

are reduced to the freezing point even as far south as the southern lines of Lake Okeechobee in Florida. The barometric changes and the temperature effects due to advance of one of these cold waves which produces freezing in all of the Gulf States are shown in Fig. 45, page 83[11] which shows the temperature and barometric condition for each of the four days from December 26 to December 29, 1894. On the 29th the temperatures at several points in Southern United States were as follows:

Mobile	16°	Jupiter	24°
Jacksonville	14°	Tampa	19°
Key West	44°		

[10] See Bulletin Q, U. S. Dept. Agriculture, Weather Bureau, "Climatology of the United States," by A. J. Henry.

[11] See Bulletin P, U. S. Dept. Agriculture Weather Bureau, "Cold Waves and Frost in the United States," by E. B. Garriott.

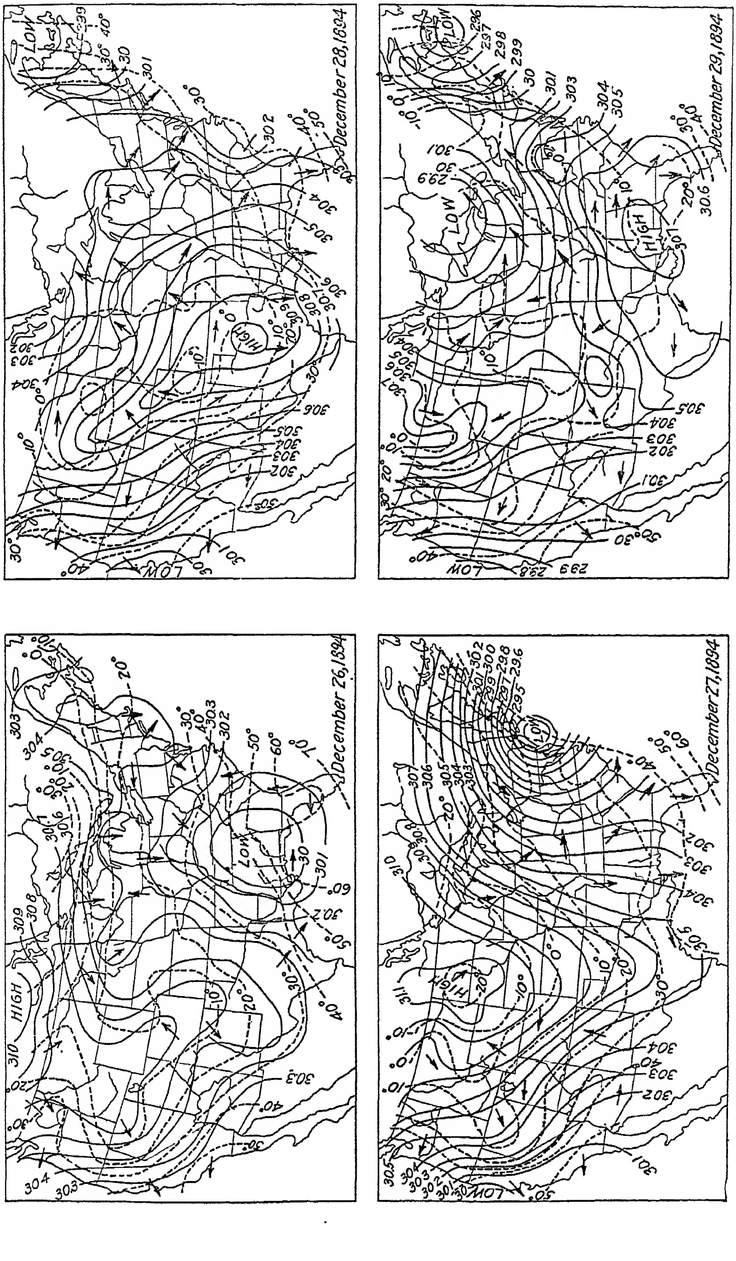


Fig. 45.—Weather Conditions in the United States during Cold Wave of 1894. From U. S. Weather Bureau Bul. P, by E. B. Garriott.

46. Hot Waves.—The movements of barometric pressure centers as indicated in Fig. 26, page 64, represent average conditions from which great variations sometimes obtain. During the summer season periods of stagnation occur in the movements of these centers. When at such times a center of high pressure rests over the southern Atlantic Ocean, with low centers over the northern Rocky Mountain region or along the northern border of the United States, the pressure distribution will normally produce high temperature conditions in the Mississippi Valley and the Atlantic States due to the southerly winds which cause a continuing flow of heated air from the Gulf of Mexico and Southern Atlantic over these regions. The series of maps, Fig. 46, page 85, show the conditions for July 1–4, 1901, and illustrate the pressure, temperature and wind conditions during an extreme hot weather period. It may be noted that at 8 A. M. on July 2, 1901, the thermometer stood at 92° in Philadelphia, 90° in Baltimore and 88° in New York City. Figure 47, page 86, shows the maximum recorded temperature in the United States.[12]

47. Hydrological Effects of the Winds.—A study of the character of the winds which occur in any locality is of importance to the hydraulic engineer on account of their effect on both precipitation and water levels. These atmospheric movements transfer such vapor as may be taken up from bodies of water, moist earth areas or areas of vegetation and deposit them again wherever the conditions are favorable for precipitation. The passage of atmospheric currents that have been relieved of their moisture, on the other hand produces evaporation and adds to aridity. Hence the normal and possible movement and paths of cyclonic storms and the resulting direction of the wind, together with the character of the surface over which the winds have passed, materially affect their rain bearing qualities. These conditions will be further considered in future chapters, as will also the subject of normal stream flow and the occasional extreme flood conditions to which they give rise.

The direct effects of the passage of storm centers on the elevation of surface waters by wind tides and storm waves are also important matters to engineers in charge of construction on or in the immediate vicinity of large bodies of water and will be considered in the next chapter.

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[12] See Bulletin Q, U. S. Weather Bureau, "Climatology of the United States," by A. J. Henry.

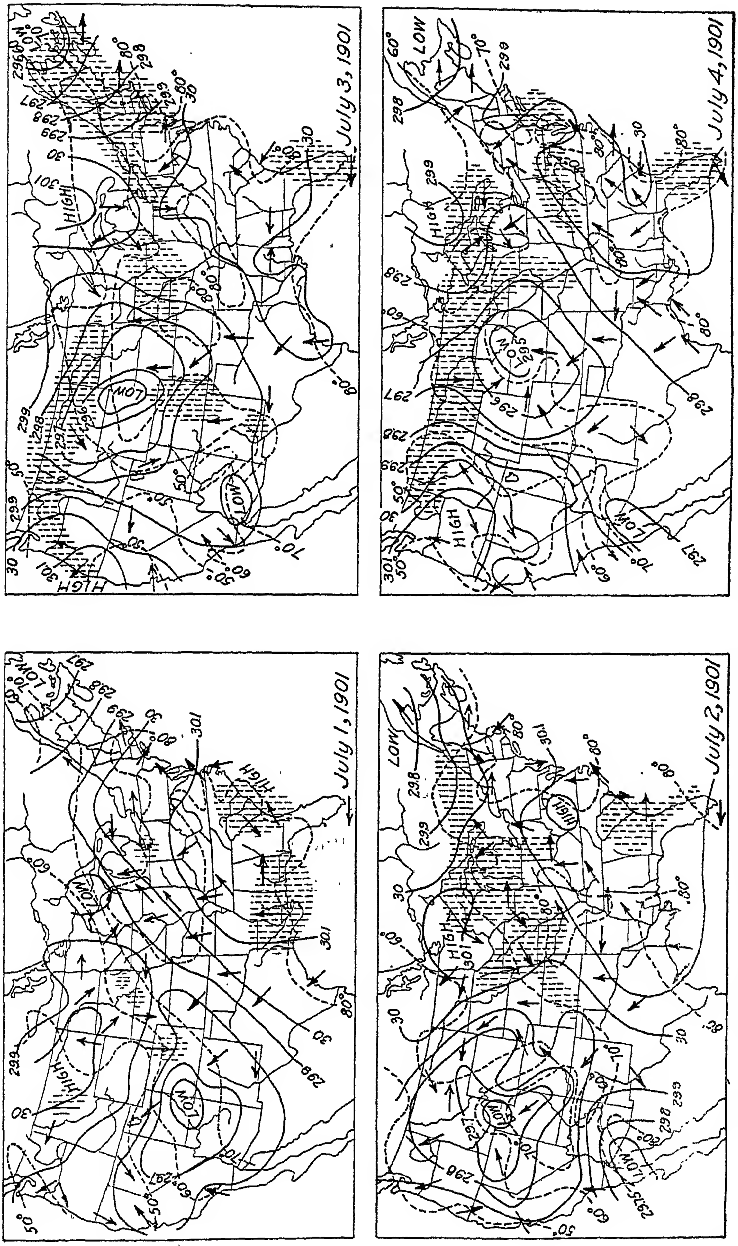

Fig. 46.—Weather Conditions in the United States during Hot Wave of 1901 (see page 84).
From U. S. Weather Bureau Bul. Q, by A. J. Henry.

48. **Weather Forecasting.**—The study of the preceding sections of this Chapter should give a fairly good idea of the basis of weather forecasting. The data from which the daily weather map is made are taken each morning at 8 o'clock, 75th meridian time, which is approximately equal to 7 o'clock at Chicago, 6 o'clock at Denver and 5 o'clock at San Francisco. The various observers at some 200 stations in the United States and the West Indies, after taking the observations for air pressures, temperatures, humidity, precipitation, wind

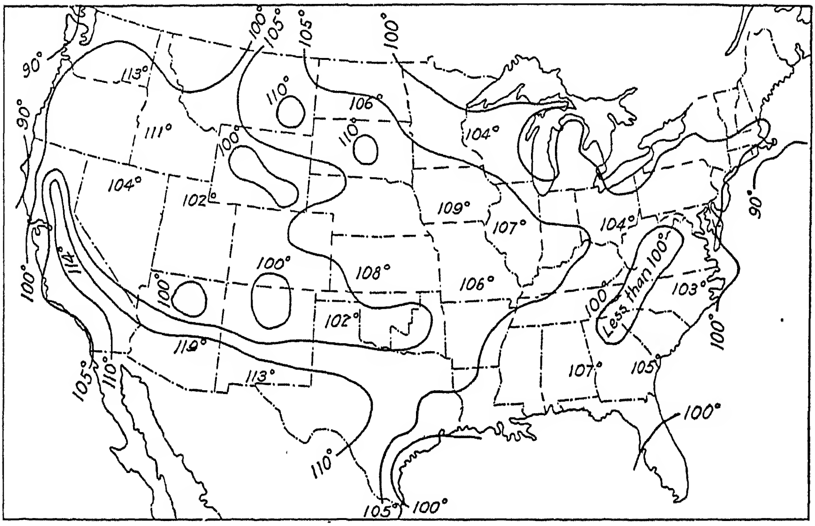

Fig. 47.—Maximum Temperatures in the United States[13] (see page 84).

direction and cloudiness, send these observations to Washington. Certain important stations also receive observations from such other stations as are required for local forecasting. In the Forecast Division at Washington, these data are assembled on various charts, including charts showing:

1st. Changes in temperatures during the preceding twenty-four hours.

2d. Changes in barometric pressure.

3d. Humidity of the air.

4th. Cloud areas.

5th. Air temperatures and pressure, velocity and direction of the wind, character and amount of precipitation since last reports, and cloudiness.

[13] U. S. Weather Bureau Bul. Q, by A. J. Henry.

On this chart, which is the general weather map familiar to the public, isobars and isotherms are drawn, the former indicating the centers from and toward which the air movements must take place.

From years of experience the forecaster knows:

1st. That high and low pressure areas drift across the country from the west toward the east in periods averaging from three to four days each and at a speed of about 600 miles per day. The average speed of movement is about thirty-five miles per hour in winter and twenty-four miles per hour in summer, for the lows, and about thirty miles per hour in winter and twenty-two miles per hour in summer, for the highs.

2d. That the lows, as they drift east, bring warmer weather and often rain or snow, while the highs which follow will bring cooler and probably fair weather.

3d. That occasionally there are periods of stagnation in the drift of the high and low areas, and that at such times there occur abnormal conditions of cold, heat or precipitation.

4th. That about forty per cent. of the storms come from the northwest and pass easterly over the Lakes and New England, usually producing but scanty rainfall.

5th. That about twenty-one per cent. of the storms come from the arid regions of the southwestern states and in their northeastward movement can usually be depended upon to produce considerable rain.

6th. That the most severe general cyclonic wind and rain storms in the United States originate in the West Indies, travel in a northwesterly direction until they reach the South Atlantic or Gulf Coast, and then recurve to the northeast and sweep along or approximately parallel the Atlantic Coast, their path being determined by the position and intensity of pressure centers to the north.

7th. That under the known conditions that exist at the time of observation the storm movements will in general follow well established paths and give rise to conditions in the next twenty-four hours that are fairly determinate.

8th. That at times accelerating forces, not indicated by the daily observations which are taken only at the bottom of the great air mass, develop unexpected energy, cause the pressure centers to pursue paths not previously indicated, or gradually dissipate the energy of the storm in a manner not foreseen in the previous daily forecast.

After the data are duly correlated on the weather map, the fore-

caster notes the changes and movements in the air conditions during the preceding twenty-four hours, and from these data he estimates what the weather will be in the different sections of the country the following day.

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CHAPTER V

HYDROGRAPHY

49. Ocean Currents.—The circulation of the water of the ocean is caused by the heating at the tropics and cooling at the poles, which induces a general surface motion poleward and a motion in the depth toward the equator which is more or less modified by the continental masses and irregularities and by the difference in the velocity of rotation of the earth at the equator and the poles. The results of these causes are ocean currents more or less restricted in the limits of their surface activity (see Fig. 48, page 91).

The ocean currents have an indirect effect on the temperature and rainfall of the various land areas eastward of the courses in which they flow. The warm ocean currents on their poleward flow increase the temperature of the superincumbent atmosphere which in drifting eastward, warms the northwestern shores of the continents. As the cold returning currents wash the eastern shores they can have practically little effect on those shores, except through their modification of the temperature of occasional ocean breezes. The modifying effect on the land temperatures of the eastward drift of the atmosphere from the ocean to the land is well illustrated by Figs. 15 and 18, pages 50 and 52, showing the isothermal lines of the Northern Hemisphere for January and July, respectively. The lines on the west coast of both Europe and North America are carried northward, while those of the eastern shores of Asia and North America are carried southward. The latter effect, however, is not due to the cold ocean currents but is a result of normal continental temperatures, the effects of which are in fact extended far to the eastward over the oceans by the normal atmospheric drift.

The effect of the ocean currents is less marked in the Southern Hemisphere due to the greater amount of water area and the consequent greater regularity in the courses of the currents and to the fact that the greater water area tends toward a more uniform distribution of heat.

50. Lake Currents.—Various factors will create currents more or less distinct in inland lakes. Among these are:

1. The general trend of the waters toward the outlet.
2. The inflow of water from streams.

3. The winds.

4. Variations in air (barometric) pressures on different portions of the lake.

5. Variation in temperature at different depths.

These factors normally result in:

a. A main current toward the outlet.

b. Surface currents due to wind and barometric gradients.

c. Return currents due to the escape of water temporarily banked up by winds or by air pressure.

d. Vertical currents caused by temperature changes.

In general, the body of water of a lake is so large relative to its outflow that the main lake currents are often obscured or reversed by winds and barometric effects. These currents are seldom so persistent and intense as to assure the continuous passage of water, with any material it may carry, in a single direction although under certain circumstances such conditions may obtain for the greater part of the time. The subject of lake currents is of particular interest and importance in the study of the distribution of polluted waters from rivers or sewers relative to water supply intakes from the same bodies into which such polluted waters are discharged.

51. Vertical Lake Currents.—In temperate climates, except during the period when lakes are ice covered, the temperature of the surface waters varies with the mean atmospheric temperature. From the breaking up of the ice in the spring, the surface waters begin to increase in temperature until about midsummer, after which they begin to cool until they reach 32° Fahrenheit in the fall with the freezing of the surface. On account of the greater density of water at 39.1° Fahrenheit, when the temperature of the surface water reaches that stage it begins to sink allowing warmer or colder water to take its place until there is an adjustment of the whole body of water in accordance with its density and so far as it can be affected by changes in density. In shallow lakes less than 20 feet in depth, this vertical circulation of water is continuous except when the surface is frozen. In large and deep lakes there is but little vertical circulation as water of maximum density rests on the bottom at all times. In lakes of intermediate depth there are two periods of vertical circulation namely in the spring and in the fall when the surface temperature changes through that of maximum density and also two periods of stagnation, namely during the summer and winter periods. This circulation is of importance relative to the

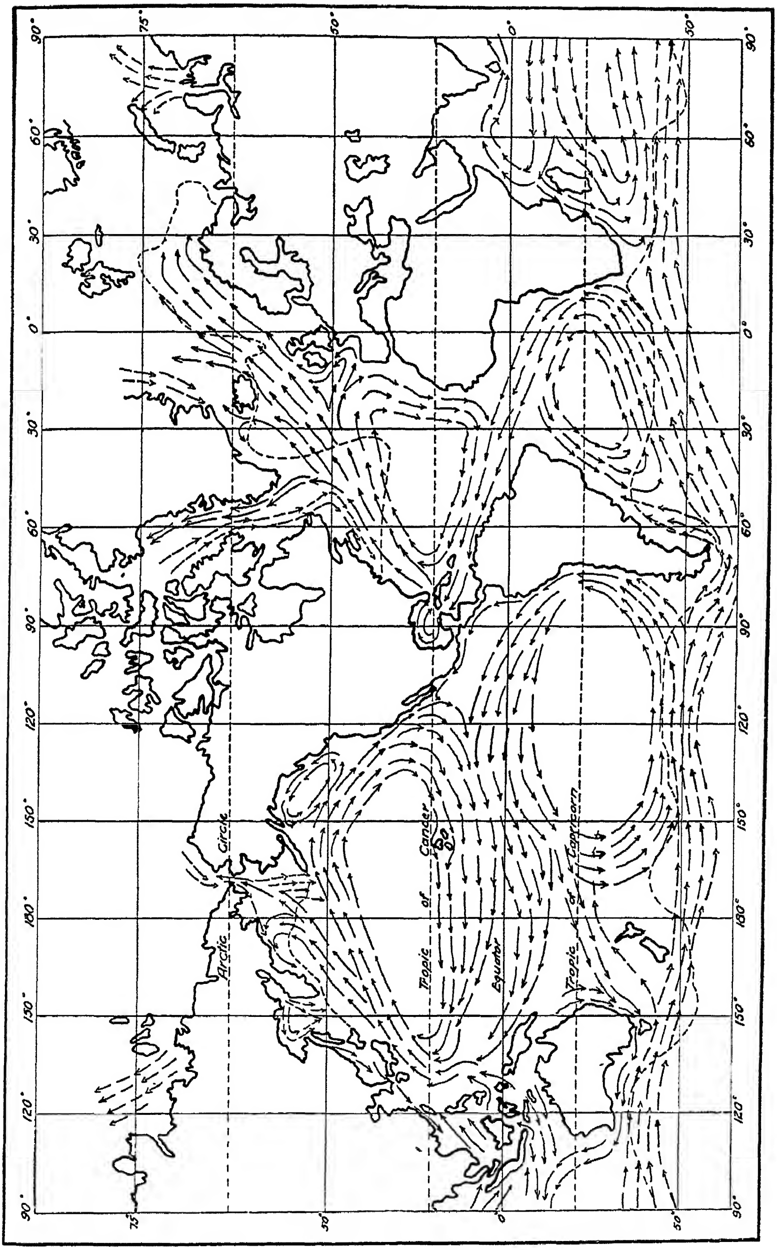

Fig. 48.—Ocean Currents of the World.

temperature and quality of water supplies which are affected by these periods of circulation and stagnation.*

52. **Tides.**—A periodical movement of the sea water which is not primarily circulatory is caused by the attraction of the sun and moon. This movement, which is manifested as a progressive wave called the tide, takes place essentially simultaneously on opposite sides of the earth. The effect of the sun is about forty per cent. of that of the moon. Due to the difference in the *differential* attraction of those two bodies, when the sun and moon act together upon one portion of the earth's surface, the high or spring tides occur and the low or neap tides result from the sun and moon acting in opposition, each condition taking place twice in each lunar month. The problems and conditions presented by the tides are of importance in many affairs, such as improvement of harbors and other coast work, determination of mean sea level datum, determination of the mass of the moon, rigidity of the earth and other geodetic research.

The investigation of the problem of the tides is exceedingly complex, since the influence of many conditions must be considered. Thus the height and speed of progression of the tidal wave are affected by the laws of wave motion, and attraction and motion of the moon, the attraction of the sun, the rotation and revolution of the earth, the inertia of the mass of water, the viscosity of the water, the friction of the water against the bottom, the irregularity of contour of the bottom, the interference and reflection of the wave due to the irregular land masses and other conditions.

According to the law of wave motion as shown by Prof. G. B. Airy, the speed of progression of the wave depends directly upon the depth of water when the length of wave from crest to crest is large in comparison with the depth, and is the same as that which a free body would acquire by falling from rest through a height equal to half the depth of water. This law is mathematically expressed as

$$v = \sqrt{gd} \tag{1}$$

where

v represents the velocity of propagation
g represents the acceleration due to gravity
d represents the depth of water

The wave can theoretically progress in synchronism with the apparent motion of the moon only when the depth is more than thirteen

*See Miscroscopy of Drinking Water, by G. C. Whipple, Chap. V; also The Temperature of Lakes, by Desmond Fitzgerald.

or fourteen miles, and since there are no such depths in the ocean the wave is forced to lag behind the point which is under direct attraction of the moon because of friction on the bottom of the sea. This lag is further augmented by the inertia and viscosity of the water itself.

Considering the great variability in contour of the bottom and the consequent changes in the amount of friction, it is easily understood that unknown and very complex factors are introduced into the problem, and the influences are rendered still more complicated by the land masses which interrupt and reflect the wave.

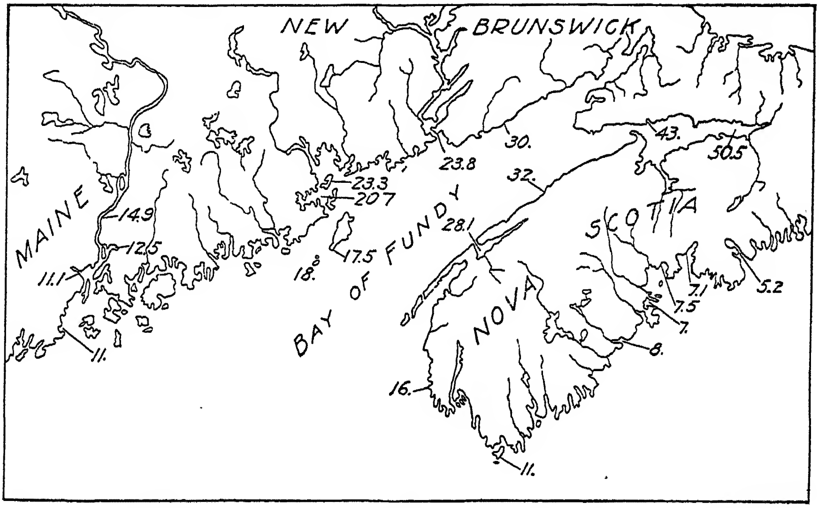

Fig. 49.—Range of Spring Tides in and near the Bay of Fundy.

In the open ocean, the tidal wave is three or four feet in height. As a wave passes from deeper to shallower water, the increased friction tends to decrease the height of the wave, while the expenditure of the same amount of energy on the small mass of water conduces to increase the height, the total result being to produce a higher wave. Under favorable conditions, the increase in height is very pronounced. Perhaps the best example of the great range in tides caused by the peculiar relation and configuration of the land and the increase toward the head of an inclosed body of water is found in the Bay of Fundy.

Figure 49, shows the range of the spring tides along the coast of Nova Scotia and the State of Maine, and the increased height toward the head of the Bay of Fundy, where an extreme of 50.5 feet is reached in Noel Bay, Minas Basin.

In the Gulf of California the rise of spring tides is about six feet at Alata near the mouth and thirty-one feet at the mouth of the Colorado River at the head of the Gulf.

"In Bristol channel the rise of spring tides at the mouth is about eighteen feet, at Swansea about thirty feet, and at Chepstow about fifty feet."[1]

Under certain circumstances, obstructions at the mouth of an estuary present a condition causing the tide to enter as one or more waves,

FIG. 50.—Hangchow Bore at Harming on the Tsien-tang River, China.[2]

known as the *eagre* or *bore*. Examples of this state are furnished by the Amazon River, which the bore ascends in three great waves thirteen to twenty-three feet in height. Figure 50, from a photograph, shows the bore in the Tsien-tang River at Harming, taken in 1914. The crest of water was vertical and about sixteen feet in height, with a second wave four feet in height so close behind that it cannot be distinguished in the picture. The river at Harming is about a mile in width and the water continued to rise for thirty minutes after the crest had passed, finally reaching a height of twenty-eight feet. The wave traveled with a high velocity. In seven minutes after it could be distinguished on the horizon the wave had passed.[2] Thus it is seen

[1] See Professional Paper No. 31, Corps of Engineers, U. S. A., p. 90.

[2] Photograph and data furnished by Mr. E. C. Stocker of Shanghai, China.

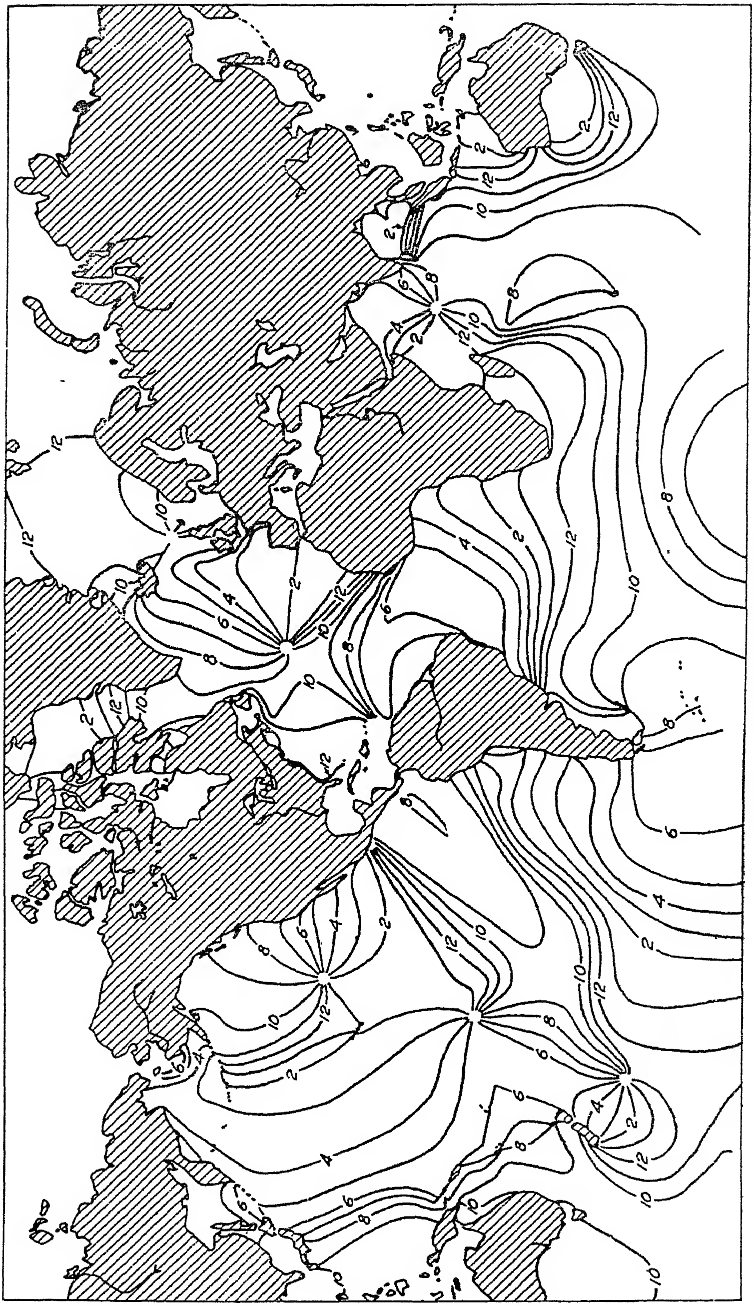

Fig. 51.—The Co-Tidal Lines.

that the height and amplitude, as well as the speed of progression of the tidal wave, are subject to great variations and complications, because of the many complex influences exerted by the great variety of existing conditions. These complications are so great as to prevent a general solution of the problem of the progress of the tide.

At any certain place the height and occurrence of the tides are predicted with a considerable degree of accuracy after the data of observations for a year or more have been collected and correlated. The accuracy of such predictions becomes more nearly exact as the more or less local influences of winds, configuration, etc., become of relatively less moment and the transit of the sun and moon bear more directly upon the time of occurrence. The computations entailed in predicting the tides are now accomplished by a complicated mechanical device known as the tide predicting machine, the latest one of which provides for thirty-seven components.[3]

Fig. 51, page 95, is a map reproduced from an article on "Cotidal Lines for the World," by R. A. Harris.[4] The lines on the map are supposed to represent the lines of simultaneous high water at each hour Greenwich time. Mr. Harris says:

"It will be noticed that there are several points from which the cotidal lines for all hours seem to radiate, and so must be points where the range of tide is zero. These points and radiating lines are caused by the overlapping of systems, by progression due to secondary or dependent bodies of water into which a free wave progresses, and by the necessity of a gradual change between adjacent regions whose tides are not simpultaneous. * * *

"It has been supposed that the tides of the ocean advanced westward around the globe, endeavoring to follow the moon in her apparent diurnal course in the heavens. A westerly progression was especially looked for in the southern areas where a continuous zone of water encircles the earth. What have we in reality? A remarkable eastward progression in the Pacific Ocean due to the opening between Cape Horn and Graham Land forming a break in the rigid boundary which constitutes the eastern support of the South Pacific oscillating system."

It is probably true that the tidal motion of the water in ocean basins is an eastward and westward swinging motion rather than a series of progressive waves as seems to be indicated by the map.

[3] U. S. Coast and Geodetic Survey Tide Predicting Machine No. 2, by E. G. Fischer, Eng. News, July 20, 1911.

[4] National Geographic Magazine, Vol. 17, p. 303, June, 1906.

Numerous other examples of the profound effect of continental configuration upon the progression or height of the tidal waves exist; among some of the most striking may be noted the case of New York Bay. The high tide at the western end of Long Island is some three hours later than that at Governor's Island in New York Harbor. This condition is produced by two waves, one of which progresses around the eastern end of Long Island and the other up East River. The meeting of these waves produces such an effect that the time of high tide differs by as much as an hour for points within a mile of each other.

Another case of complication is that of Lynn Canal, Alaska, near Sitka. This canal is about 100 miles in length and extends in a northward direction. The time of high tide occurs at the upper end at about the same time as that at the mouth. This occurrence is attributed to reflection of the wave from the inner end.

Table 3 gives the range in spring and neap tides at various important points throughout the world.

TABLE 3.

Tide Table.

	Range of Tides.	
AMERICA	Spring.	Neap.
St. Johns, Newfoundland	3.3	1.5
Halifax, Nova Scotia	5.2	3.2
Pubnico, Mouth, Bay of Fundy	12.0	8.9
Noel Bay, Minas Basin Head, Bay of Fundy	50.5	37.4
Rockland, Mouth, Penobscot Bay	11.0	8.2
Bucksport, Penobscot River	12.5	9.4
Bangor, Penobscot River	14.9	11.1
Boston, Navy Yard	10.9	8.1
Pleasant Bay, Cape Cod	4.1	2.9
New York, The Battery	5.3	3.4
Philadelphia, Pennsylvania	5.6	4.9
Washington, D. C	3.3	2.4
Old Point Comfort, Virginia	3.0	2.0
Cape Hatteras, North Carolina	4.2	3.1
Miami, Key, Biscayne Bay, Fla	1.3	0.9
Key West, Florida	1.6	0.9
Tampa, Florida	2.9	1.4
Port Eads, Louisiana	.2	.1
Galveston, Texas	.7	.4
Havana, Cuba	1.3	0.7
Colon, Panama	1.1	0.6
Balboa, Panama	16.2	8.7
Maraca Island, Brazil	30.0	14.3
Entrance, Amazon River, Brazil	14.3	6.8
Altata, Mouth, Gulf California	5.8	1.4

TABLE 3.—*Tide Table*—Continued.

	Range of Tides. Spring.	Neap.
Mouth, Colorado River, Head, Gulf California	31.5	7.3
San Diego, California	5.2	2.3
San Francisco, California (Presidio)	4.9	3.1
Columbia River, Bar	7.6	4.4
Seattle, Elliott Bay	9.1	5.9
ASIA		
Nagasaki, Japan	8.4	3.4
Yokohama, Japan	4.8	1.9
Shanghai, China, Wusung Bar	9.2	4.9
Hangchow Bay, China	13.7	7.2
Amoy, China	15.6	9.8
Hong Kong, China	4.4	2.1
Bombay, India	14.2	11.2
EUROPE		
Aberdeen, Great Britain	12.	10.
Avonmouth, Great Britain	38.	28.
Belfast, Great Britain	9.5	7.5
Bristol, Great Britain	33.	23.
Cardiff, Great Britain	36.5	27.
Cork, Great Britain	12.7	10.
Dover, Great Britain	18.7	15.
Glasgow, Great Britain	12.2	9.2
Hull, Great Britain	20.7	16.2
Liverpool, Great Britain	27.5	20.2
London, Great Britain	20.7	17.2
Queenstown, Great Britain	11.7	9.
Southhampton, Great Britain	13.	9.5
Bordeaux, France	15.5	12.
Calais, France	21.	17.5
Antwerp, Belgium	16.7	
Rotterdam, Holland	7.	
Hamburg, Germany	6.2	5.5
Christiana, Norway	1.5	
Gibralter	3.2	2.5
MISCELLANEOUS		
Alexandria, Egypt	1.	.3
Zanzibar, Africa	15.	10.
Natal, Africa	6.5	3.7
Honolulu, Hawaiian Island	1.5	0.8
Manila, River Entrance, P. I.	1.8	0.9

53. **Wind Tides.**—The directions and intensities of the winds have an important influence on tides, waves and consequent water elevations. The effects of easterly and westerly winds on the surface of Lake Erie, the longitudinal extension of which lies in the direction of the easterly path of storm centers (see Fig. 52, page 99) is to produce at times great variation in the surface elevation at the easterly and westerly ends of the lake (see Fig. 53, page 100).[5] The intense winds

[5] Bulletin J, U. S. Weather Bureau, "Wind Velocities and Fluctuations of Water Level on Lake Erie," by Prof. A. J. Henry.

known as hurricanes and typhoons that occur in the West and East Indies, respectively, occasionally greatly endanger the safety of cities and farm lands which are exposed to such effects. The effects of the West India hurricane of 1909 on the elevation of the water surface in the lakes and bayous of southern Louisiana near the mouth of the Mississippi River are shown on Fig. 54, page 101.

Much of the loss of life and property in the hurricanes of September, 1900, and of August, 1915, at Galveston (see Fig. 42, page 80), and along the coast of Texas, was due to the high wind tides

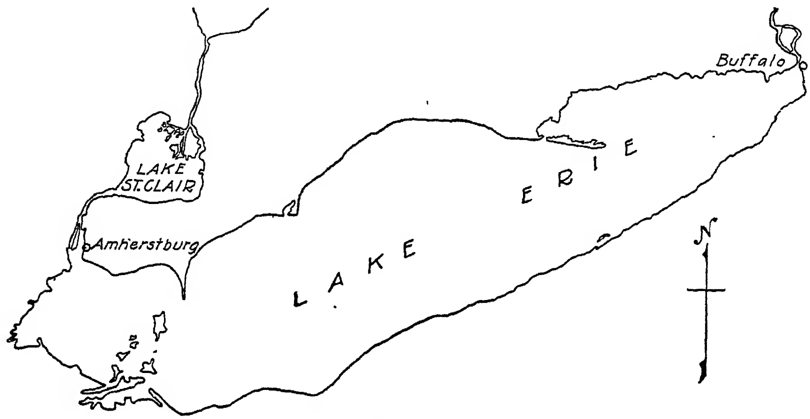

FIG. 52.—Map of Lake Erie.

that were caused by the passage of these storms. The tremendous direct attack of the waves accompanying these high tides can be resisted only by the strongest class of masonry construction. The high waters in the interior rivers, bayou and lakes can often be overcome by levee construction, properly protected at points exposed to wave wash.

In the storm of November 21, 1900, the wind at Buffalo attained a maximum velocity of 80 miles per hour and the lake level rose to 120 inches above zero while at Amherstburg, Ontario, near the western end of the lake, the water level reached a stage 33 inches below zero.

54. **Seiches.**[6]—Seiches are oscillations of the water surfaces of lakes above and below mean lake level. They have an amplitude of from a few inches to occasionally several feet, and are supposed to be occasioned by changes in barometric pressure. Small rythmic oscilla-

[6] See Notes on the Hydrology of the Great Lakes, by P. Vedel; vol. 1, Jour. Western Society of Engineers, p. 426 et seq.; see also Enc. Brit. article on lakes.

tions of a few inches in amplitude frequently occur on Lake Superior within a period of about ten minutes; on Lake Michigan similar oscillations from the east to the west, with a period of about fifteen minutes, are frequently observed. The periods of these oscillations are too short for transition from shore to shore across the lake basins, but oscillations of longer periods and of greater amplitude have been observed

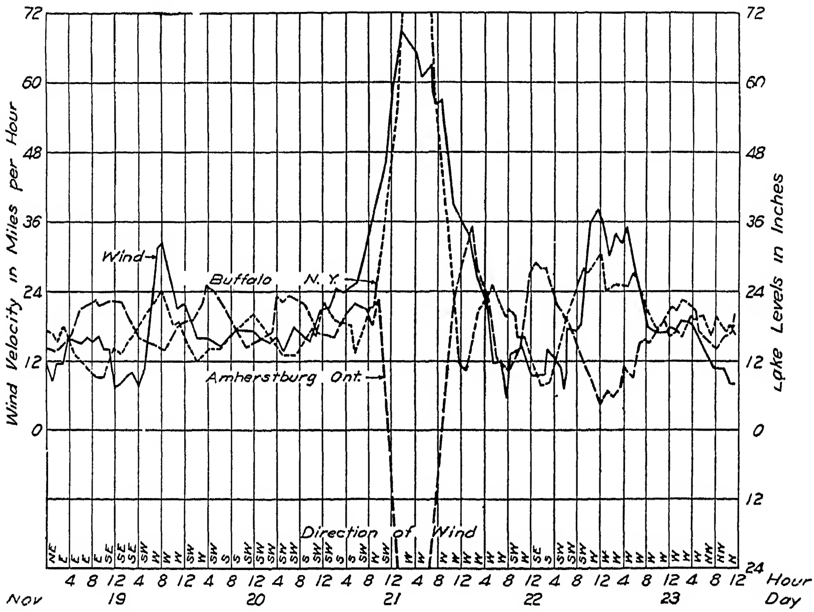

Fig. 53.—Wind Velocities and Water Level Fluctuations on Lake Erie, November, 1900 (From Bul. J, U. S. Weather Bureau) (see page 99).

between Milwaukee and Grand Haven where such oscillations have occurred eleven times in twenty-four hours.[7] These oscillations were extensively studied early in the nineteenth century in connection with the Swiss lakes.[8]

Seiches of unusual height have occasionally been observed. One seiche was observed in Lake Geneva in October, 1841, which was seven feet high, and in Lake Superior, in 1854, a seiche of unusual height was said to have left the St. Mary River nearly dry for about an hour.

On August 16, 1886, a similar series of oscillations occurred in Lake Michigan, caused by an area of low pressure passing over the lake and continued for about 24 hours. An automatic gage record of the varia-

[7] See Annual Report Chief of Engineers, U. S. A. 1872.

[8] See Nature, p. 18, 1878.

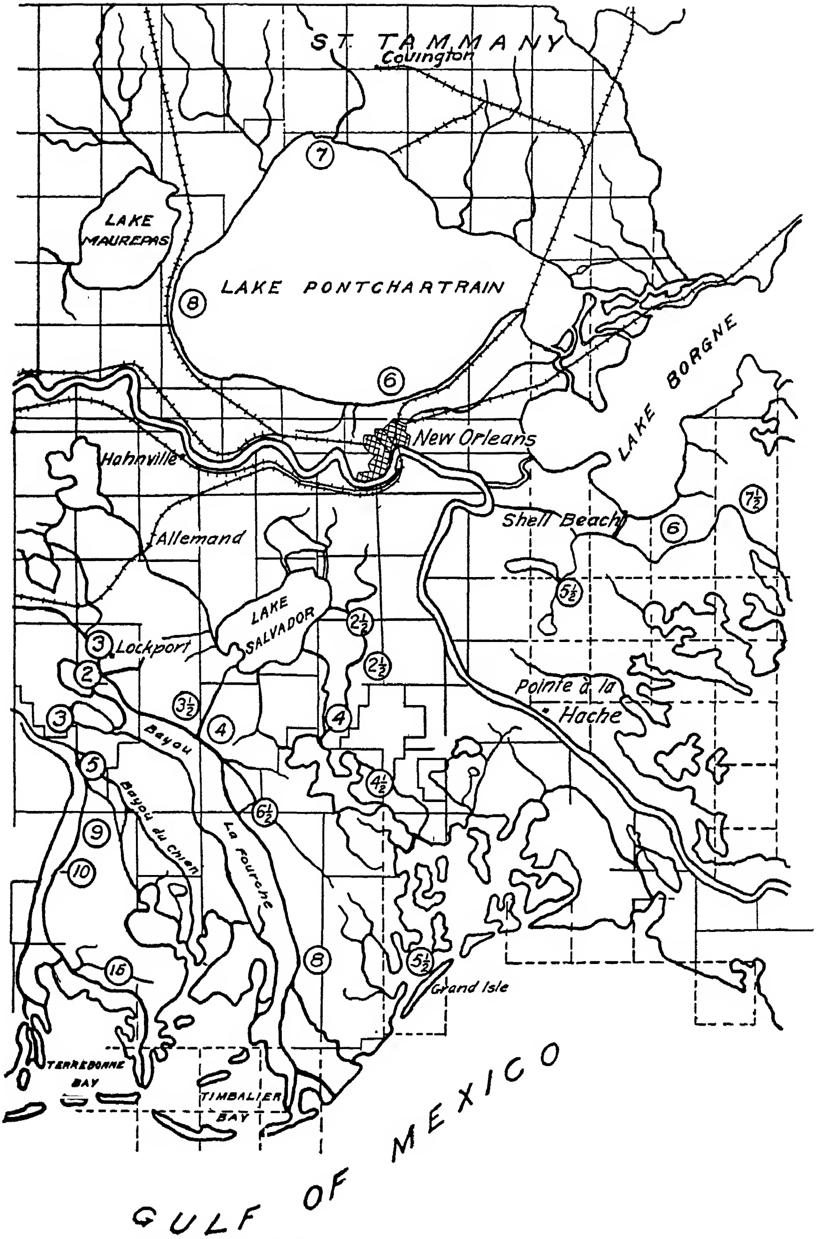

Fig. 54.—Hurricane Tide Effects in Southern Louisiana, 1900 (from a map by Mr. A. M. Shaw, published by the U. S. Dept. of Agriculture) (see page 99).

tions in the lake level at Chicago on this date was published in the report of the Survey of the Waterway from Lake Michigan to the Illinois River by Major Marshall. The curve shows regular 15 to 20 minutes oscillations the amplitudes of which are a few inches, but combined with these oscillations are others of a larger amplitude with a period of about 40 minutes. Twenty-six waves occurred in an 18 hour period, the greatest waves having an amplitude of two feet ten inches, the surface falling this distance in 15 minutes. The largest seiche in Lake Michigan occurred on April 7, 1893, and was noted simultaneously at Chicago and St. Joe, Michigan, rising to heights of from four to six feet.

Fig. 55,[9] is the record of an automatic U. S. L. S. gage located at the head of the St. Clair River and at the outlet of Lake Huron,

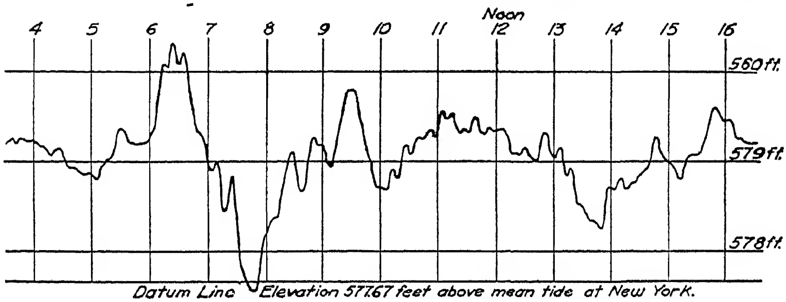

FIG. 55.—Seiches on Lake Huron.

and illustrates the occurrence of seiches caused by barometric pressure changes on the southern end of Lake Huron.

55. **Waves.**—On account of the characteristics of mobility and viscosity a disturbance to any one of the particles of a body of water is transmitted to contiguous particles and thence to others more remote, causing ripples, oscillatory movements or movements of translation known as waves. The wave is a disturbance of the surface in the form of a ridge or depression and is propagated by certain forces which tend to restore surface equilibrium. In general the particles of water do not advance materially with the wave.

Ripples are the smallest class of waves in which the surface tension of the water is the principal motive force of restoration of the particles.

Oscillatory waves are similar to ripples, except that the motive force of restoration is principally due to gravity. These waves always occur

[9] From Report on the North and Northwestern Lakes, by Col. G. J. Lydecker. Appendix 111, Report of Chief of Engineers U. S. A. for 1900.

in groups and are raised partly above and are partly depressed below the undisturbed water level.

Waves of translation are wholly raised above or depressed below the undisturbed water level. Those raised above the general level are termed *positive* waves and those depressed below this level are termed *negative* waves. Such waves are propagated as a single hump or hollow passing over the still water surface. In this wave there is not only a progressive movement of the wave form, but also a translation of the particles of water for a short distance in the direction of motion.

Waves may be classified as wind waves, tidal waves or those produced by sudden disturbances, such as by earthquakes. The great waves sometimes caused by earthquakes are the most serious in their destructive effects but are too uncertain in their occurrence, extent and action to admit of investigation.

56. **Wave Motion.**—A ship at sea which encounters great waves moving at a high velocity across its course is not appreciably moved from its course but simply rises as the wave crest passes and then sinks in the trough which follows. Floating objects near the land rise and fall in the same manner as the wave passes, move in or out with the tide, or in the direction of local currents, showing that wave motion is quite different from the motion of the water in which it moves.

"If a body floating upon the surface of the water be observed carefully, it will be seen to rise, move forward, and sink when on the upper portion of the wave, and to continue to sink, move backward, and rise again when on the lower portion of the wave, but without appreciable movement in the direction of wave travel, except such as may be due to the action of wind or of currents. Each particle moves about its position of rest in a closed orbit, in a manner consistent with the movement of all other particles in the wave. How this is accomplished is shown in Figs. 56 and 57, page 104, which are modifications of Webers' diagram of an oscillatory wave; the particles moving in circular orbits in the same direction as the hands of a clock, and the wave advancing in the direction shown by the arrow. *a, b, c, d, e, f, g, h,* etc., Fig. 57, represent horizontal, and *k, l, m, n, o, p, q,* etc., vertical filaments of water in a state of rest. The positions of the corresponding filaments during the passage of a wave are shown in Fig. 56. In this figure the filament *a* is represented by the common cycloid, and all other horizontal filaments by prolate cycloids. The dimensions of the orbits of the particles decrease rapidly below the surface, as indicated by the limiting lines *rx* and *rw* in the figure.

"Those particles which lie in the same vertical filament when at rest, arrive at the lowest point of their orbits at the same instant when wave motion is in progress, taking the position shown at *q*. When the wave advances, the filament takes successively the positions *p, o, n,* etc., the upper portion bending over toward the wave crest until at *k,* directly under the crest, it becomes vertical. After the crest has passed, the filament again inclines toward it until the next succeeding trough arrives, when it again becomes vertical.

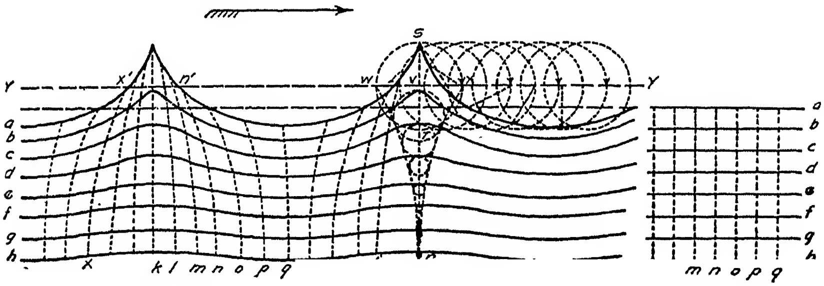

Fig. 56 Fig. 57.

Wave Action.[10]

"When the wave occupies the position shown in Fig. 56, all particles between the filaments *xx'* and *nn'* have motion in the direction of wave travel, and those between *nn'* and *ii'* in the contrary direction."

"Shallow water waves" are those that occur in water of a depth less than half the wave length. In such waves the orbits of its particles are elliptical instead of circular. In very shallow water the ellipse approaches a straight line in form."[10]

57. **Height of Oscillating Waves.**—The height of a wave is the vertical distance from its highest to its lowest point. Oscillating waves will attain their maximum only in waters of adequate depth and no such wave will reach a height greater than the depth of water through which it passes. Mr. Thomas Stevenson established from numerous observations a formula for the height of wave in feet relative to the "fetch" or distance in nautical miles[11] to the windward shore as follows:

$$h = 1.5\sqrt{f} \qquad (2)$$

where h = height in feet

f = fetch in nautical miles.

[10] See Professional Paper No. 31, Corps of Engineers, U. S. A., by Capt. D. D. Gaillard.

[11] The nautical mile = 6,080 feet = 1.15 statute miles.

It is evident that the maximum storms may not come from the direction having the maximum fetch and that, therefore, calculations based on the maximum fetch are often greater than will be realized. It must also be noted that heavy rollers as they approach a shore are deflected by the retardation due to shallowing water and become more nearly parallel with the shore or even change their direction entirely through the influence of islands or headlands.

As the height of waves seldom exceeds forty-five feet, there is evidently a limit to the influence of the fetch, which in this case would correspond to 900 miles, while the width of the ocean may be several thousand miles. From the previous chapter it is evident, however, that, as most ocean winds have a rotary direction, it is seldom that violent winds follow approximately a straight course of more than 900 miles.

For short distances (of perhaps two miles or less) and violent squalls, Stevenson proposes the formula

$$h = 1.5\sqrt{f} + (2.5 - \sqrt[4]{f}) \qquad (3)$$

Hawksley[12] determined by observation that the height of waves in feet h produced in large reservoirs by the heaviest gales in England could be represented by a formula that reduces to

$$h = .025\sqrt{l} \qquad (4)$$

where l = the fetch in feet, or

$$h = 1.95\sqrt{f} \qquad (4a)$$

58. Length and Velocity of Oscillating Waves.—The length of waves seems to be related to the fetch, but is independent of the wave height. Waves in the Atlantic are said to be 500 to 600 feet between crests, and in the Pacific occasionally reach 1,000 feet. Lieutenant Paris of the French navy found the ratio of length to height of wave $\frac{l}{h}$ was on an average 39 in light seas, 21 in rough seas and 19 in heavy seas.

In deep water the velocity of the wave is independent of the depth and is essentially equal to that acquired by a body falling through a height eight per cent. of the wave length and is given by the formula[13]

$$v = \sqrt{\frac{gl}{2\pi}} = \sqrt{5.12\,l} = 2.26\sqrt{l} \qquad (5)$$

Rankine states that in shallow water (i. e., water of a depth less than one-half the wave length) the velocity is equal to that of a body falling

[12] Proceedings Inst. C. E., Vol. XX, page 361.
[13] See "Wave Action" by Gaillard.

through a height equal to half the depth d of water plus three-fourths of the wave height h and is given by the formula[13]

$$(6) \qquad = \sqrt{2g\left(\frac{d}{2} + \frac{3h}{4}\right)} = 4.012\sqrt{2d + 3h}$$

Gaillard found this formula to give results considerably in excess of the observed velocities.

The agreement of the calculated with the observed height of waves is shown by Table 4. It should be noted that the storm observed may not have been the maximum storm which might be expected, hence the observed height may not be a maximum.

TABLE 4.

Comparative Observed and Calculated Wave Height.[13, 14]

Location.	Fetch in nautical miles.	Observed height.	Calculated height by formula.		
			(2)	(3)	(4)
*Duluth Basin	.375	1.5		2.6	1.2
*Duluth Basin	.428	2.3		2.7	1.3
*Duluth Basin	.641	2.0		2.8	1.6
*Duluth Basin	.748	3.8		2.9	1.7
*St. Louis Bay	.916	2.0		2.9	1.9
*Portage Lake	1.086	3.0		3.1	2.0
Firth of Forth	1.3	1.8		3.0	2.2
*St. Louis Bay	1.923	4.5		3.4	2.7
*Stannard Rock	41.45	11.	9.7		
San Pedro Bay, Cal.......	15.64	7.0	5.0		
Marquette, Mich.	116.63	15.0	16.2		
*Portage Break Water.....	82.50	16.5	13.6		
*Duluth Canal	258.62	23.0	24.1		
Clyde	9.0	4.0	4.5		
Lake Geneva	30.0	8.2	8.2		
Sunderland	165.0	15.0	19.3		
Petershead	400.0	22.6	30.0		

*Lake Superior.

Cunningham also gives the following as the recorded height of waves in heavy storms:

Lake Geneva	10 feet
German Ocean	12 to 15 feet
Mediterranean Sea	15 to 20 feet
Bay of Biscay..	25 to 30 feet
Atlantic Ocean	30 to 40 feet
Pacific Ocean*	50 to 60 feet

* Off Cape Horn and Cape of Good Hope.

A wave encountering a current in the opposite direction is increased in height; so also is a wave advancing in a channel either of uniform depth and decreasing width or of uniform width and decreasing depth. The effect of decreasing breadth and depth is well illustrated by the

[14] See "Harbor Engineering" by Cunningham.

increase in the tide wave in bays and channels like the Bay of Fundy or the Gulf of California, where the rise in tide at the head is several times greater than the rise at the mouth.

When a wave travels from deep water into water the depth of which is gradually decreasing, a change in form takes place. Due to friction upon the bottom, the velocity and length of the wave decreases, while the wave height for a time increases. The front of the wave becomes gradually steeper and the velocity of its lower portion decreases until the greater velocity of the particles at the crest carries them forward, and the crest falls over, breaking into a foaming mass of water. In such cases the wave is transformed from a purely oscillatory to a wave of translation, and the forward motion of the particles is equal to the velocity of the wave. Under these conditions the wave exerts its maximum power.

The height reached by waves breaking against headlands and structural or protecting works rises by impact to much greater heights than those estimated above. Cunningham gives the following observations on such waves:

The Hague	75 feet
Bell Rock	100 feet
Eddystone Lighthouse	150 feet
S. W. Coast of Ireland	150 feet

The element of waves, often of greatest importance in connection with engineering works along the oceans and lakes, is the height to which they will rise above mean still water. For this height Gaillard gives the equation

$$a = \frac{h}{2} + C^1 \frac{h^2}{l} \qquad (7)$$

in which a is the height of the wave above mean still water, h the total wave height, l the wave length, and C' is a coefficient, found to be about two for a mean depth of twenty-six feet in the Duluth Canal and believed to be constant for any particular location.

59. **Energy and Pressure of Waves.**—The total energy E of a wave exerted throughout its entire length (in foot pounds) and for one foot in breadth is equal to

$$E = 8\, lh^2 \left(1 - 4.9 \frac{h^2}{l^2}\right) \qquad (8)$$

The maximum pressure P of a water jet impinging against a square foot of area is

$$P = c \frac{wv^2}{2g} \qquad (9)$$

in which w equal the weight of a cubic foot of water and c is a coefficient having a maximum value of not exceeding 2. For sea water w is approximately $2g$ and c may be taken as 1.6; hence Equation 9 becomes

$$(10) \qquad P = 1.6\, v^2$$

For breaking waves Galliard found that the velocity of the waves was increased by the orbital velocity of surface particles so that under these conditions the pressure would approximate

$$(11) \qquad P = 2.3\, v^2$$

Galliard measured with dynamometer pressures as high as 2,370 pounds per square foot at the end of the Duluth Canal in Lake Superior. Cunningham gives the maximum pressure of sea waves actually recorded by dynamometer as three and one-half tons per square foot.

60. **Effects of Waves.**—The effect of ocean waves depends upon the exposure of the location to extended seaway over which heavy windstorms sometimes occur. Professor G. B. Airy shows that in the open sea when the depth is great in comparison with the length of the wave, the motion of the water at considerable depth below the surface decreases in geometrical progression and at depths equal to the length of the wave is less than .02% of the surface movement. When, however the length of the wave is great in comparison with the depth, as in the case of tide waves, the horizontal motion is the same from the surface to the bottom. The perceptible agitation sometimes extends to depths of almost 100 feet. It is asserted by pilots and masters of vessels that in times of storms off Nantucket Shoals the sea frequently leaves sand on deck, although the depths are from seventy-five to ninety feet.

The presence of mud in the bottom is a clear indication of the absence of wave action, as mud is readily eroded and washed away by such action. The absence of mud is not an indication of wave action as conditions may not have been favorable for its formation. In various lake harbors in the United States Galliard states that the mud bottom of the deeper water changes to sand at the following depths:

Duluth, Minnesota	Lake Superior	55 to 60 feet
Chicago, Illinois	Lake Michigan	40 to 45 feet
Milwaukee, Wisconsin	Lake Michigan	40 to 45 feet
Cleveland, Ohio	Lake Erie	33 to 38 feet

Any construction or barrier exposed to the attack of waves must be strong enough to resist them and to withstand the energy developed

when the wave progress is arrested wholly or in part or its destruction will ensue. The force of the waves is the most severe of any force of equal intensity to which a structure may be subjected, for as Galliard states it is exerted and transmitted in the following ways, viz.:

First.—By static pressure due to the head of the column of water.
Second.—By the kinetic effect of the rapidly moving water.
Third.—By the impact of bodies floating upon the surface and hurled by the wave against the structure.
Fourth.—By the partial vacuum due to the rapid subsidence of the wave, producing sudden pressure from within.

The effects of these shocks may be transmitted through joints or cracks, first by hydraulic pressure, second by pneumatic pressure, and third by vibrations of the material in the structure.

In the Wick breakwater, concrete blocks weighing from 80 to 100 tons and lying from five to ten feet below low water, were swept away, while eighty ton blocks lying ten to sixteen feet below low water were unmoved. At Coos Bay, Oregon, blocks of stone weighing over ten tons have been washed off the jetty above high tide by storm waves.

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CHAPTER VI

ATMOSPHERIC MOISTURE AND EVAPORATION

61. Atmospheric Moisture—Tension and Weight.—The atmosphere always contains moisture or water vapor which unless condensed as fog, clouds, etc., is transparent like the other components of the air. The maximum amount of vapor which can be contained in a cubic foot of space is limited by and increases with the temperature. At any given temperature a cubic foot of space or of air will hold only a certain maximum amount of moisture, under which conditions it is said to be saturated. The weight of moisture contained in a cubic foot of space expressed in grains is termed the *absolute humidity*. The *relative humidity* is the percentage of saturation, complete saturation being 100 per cent.

The amount of vapor in a cubic foot of space is independent of the presence of air except as the circulation of air accelerates or retards its formation. As moisture is received into the atmosphere a portion of the air is displaced thereby and the combined weight of air and vapor is less than the weight of dry air. A certain amount of vapor in a given space will possess a certain tension (or produce a certain pressure) according to the temperature. The weights of a cubic foot of dry air, of a cubic foot of saturated space, of a cubic foot of the air in a mixture of air and saturated vapor, and the corresponding weights of the mixture, together with the vapor tension and pressure of the air in a mixture of air and vapor are shown in Table 5, page 113, and the same relations of weights are shown graphically in Fig. 58, page 114.

Vapor tension is not a measure of the total amount of water vapor in the atmosphere overhead, but indicates the amount of water contained in the air. For complete saturation the relations between the weight of moisture in the air (w), in grains per cubic foot, to the vapor tension (p) in inches of mercury at any given temperature (t) above the freezing point (32° F.) is given by the formula reduced from Regnault's experiments by Broch.[1]

$$w = \frac{11.73\,p}{.9347 + .00204\,t} \tag{1}$$

Below the freezing point vapor tensions do not agree with Regnault's experiments but have been determined by Marvin.[2]

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1 See Smithsonian Meteorological Tables, p. XXXVII.

2 See Smithsonian Meteorological Tables, p. XXXVI.

TABLE 5.

Weights of Air, Aqueous Vapor, and Saturated Mixtures of Air and Vapor at Different Temperatures, Under the Ordinary Atmospheric Pressure of 29.921 Inches of Mercury

Temperature Degrees Fahr.	Weight of cubic ft. of Dry Air at Different Temperatures, Lbs.	Elastic Force of Vapor Inches of Mercury	MIXTURE OF AIR SATURATED WITH VAPOR.			
			Elastic Force of the Air in Mixture of Air and Vapor Inches of Mercury	WEIGHT OF CUBIC FOOT OF THE MIXTURE OF AIR AND VAPOR		
				Weight of the Air. Lbs.	Weight of the Vapor, Lbs.	Total Weight of Mixture Lbs.
0	.0864	.044	29.877	.0863	.000079	.086379
12	.0842	.074	29.849	.0840	.000130	.084130
22	.0824	.118	29.803	.0821	.000202	.082302
32	.0807	.181	29.740	.0802	.000304	.080504
42	.0791	.267	29.654	.0784	.000440	.078840
52	.0776	.388	29.533	.0766	.000627	.077227
62	.0761	.556	29.365	.0747	.000881	.075581
72	.0747	.785	29.136	.0727	.001221	.073921
82	.0733	1.092	28.829	.0706	.001667	.072267
92	.0720	1.501	28.420	.0684	.002250	.070717
102	.0707	2.036	27.885	.0659	.002997	.068897
112	.0694	2.731	27.190	.0681	.003946	.067046
122	.0682	3.621	26.300	.0599	.005142	.065042
132	.0671	4.752	25.169	.0564	.006639	.063039
142	.0660	6.165	23.756	.0524	.008733	.060873
152	.0649	7.930	21.991	.0477	.010716	.058416
162	.0638	10.099	19.822	.0423	.013415	.055715
172	.0628	12.758	17.163	.0360	.016682	.052682
182	.0618	15.960	13.961	.0288	.020536	.049336
192	.0609	19.828	10.093	.0205	.025142	.045642
202	.0600	24.450	5.471	.0109	.030545	.041445
212	.0591	29.921	0.000	.0000	.036820	.036820

The ratio $\frac{w}{p}$ is practically constant for small ranges of temperature but varies for temperatures from −20° to 100° F. as shown graphically in Fig. 59,[3] page 115.

The relations of absolute and relative humidity to the temperature and weight of moisture in the air are given in Fig. 60. From this diagram the relation of absolute moisture to absolute or relative humidity at various temperatures can be determined. For example: if air at 100° F. contains six grains of vapor, it is practically thirty per cent. saturated. If the temperature of the air falls to 72° F., the percentage of saturation will reach approximately seventy per cent. and if the

[3] The ratios of weight to vapor tension (Fig. 59) and the weights of saturated vapor per cubic foot of air (Fig. 60) are calculated by Formula 1 for temperatures above 32° F. and are taken from the tables of the Weather Bureau (Psychrometric Tables, Table XII, p. 83, by C. F. Marvin. U. S. Weather Bureau W. B. No. 225) for ratios below 32° F.

temperature falls to 62° F. the air will be over saturated, the dew point will be passed and condensation will begin. When air is partially saturated and its temperature is reduced, the percentage of saturation will increase, and when the saturation reaches 100 per cent. the invisible vapor will begin to condense into visible moisture. Under these conditions the corresponding temperature is called the dew point.

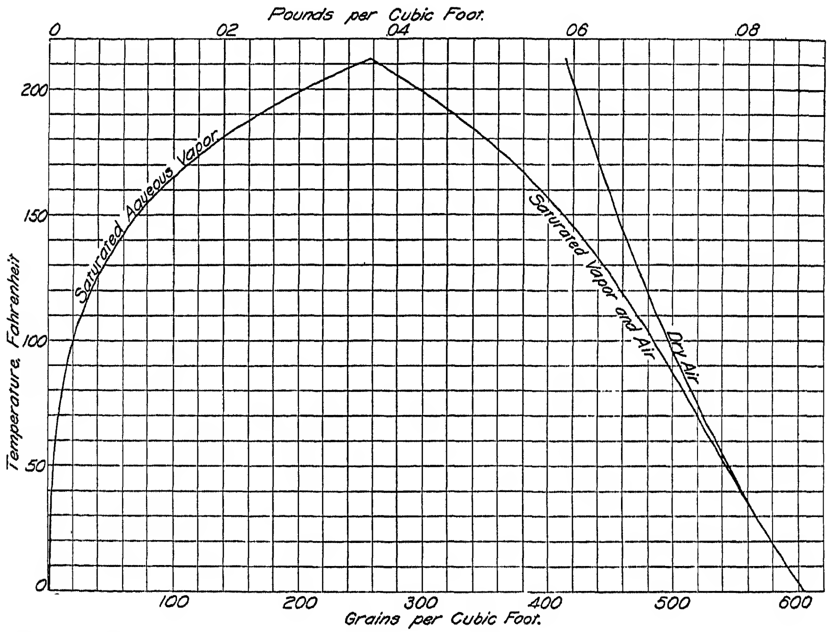

Fig. 58.—Weight of Air and Saturated Aqueous Vapor at Normal Sea Level Pressure for Various Temperatures (see page 112).

The dew point may therefore be defined as the temperature of the atmosphere at which, with the amount of vapor it contains, it will become saturated.

62. Atmospheric Temperatures and Moisture at High Altitudes.—In general the temperature of the atmosphere at all seasons of the year decreases with the altitude (see Sec. 32), except at moderate elevations (below 10,000 feet) where atmospheric disturbances sometimes cause a temporary reversal of this condition (see Fig. 61, page 116). Fig. 62,[4] page 117, illustrates the temperature gradients as they commonly exist during summer (Curves 1 to 4 inclusive) and winter (Curves 5 and 6). The straight line numbered 8 shows the

[4] See Bulletin Mt. Weather Observatory, Vol. II, part 1, 1909, p. 4.

adiabatic gradient for dry air and line 7 shows the temperature gradient for saturated air, starting with an assumed summer sea level temperature of 68° F., while lines 9 and 10 indicate the same gradients for

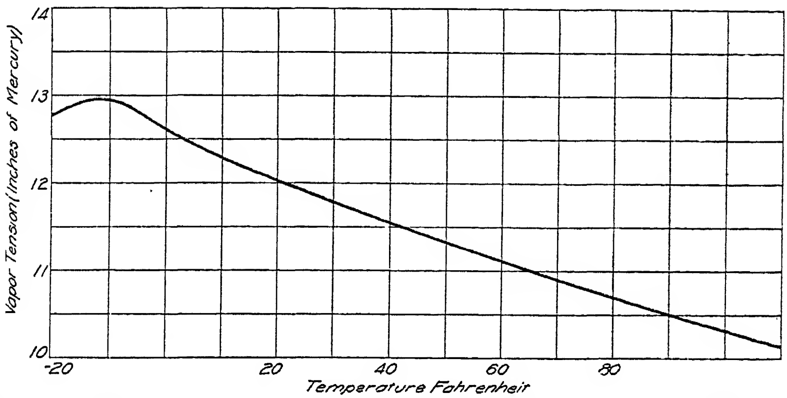

FIG. 59.—Ratios of the Weight of Vapor in the Atmosphere to Vapor Tension at Various Temperatures (see page 113).

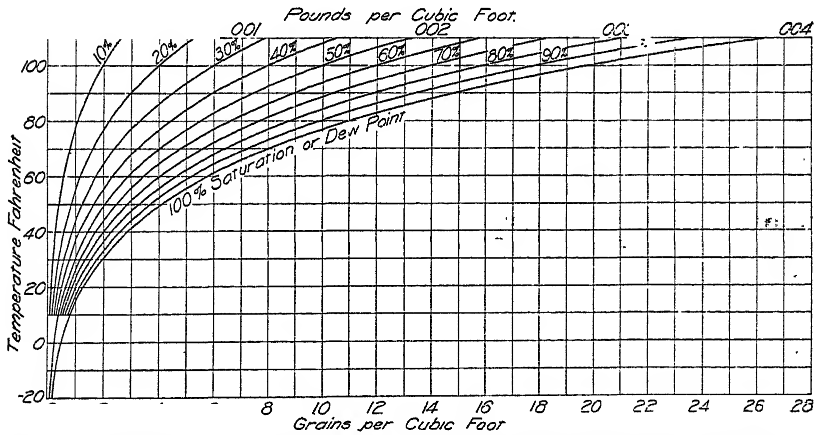

FIG. 60.—Weight of Aqueous Vapor at Various Temperatures and Degrees of Saturation (see page 113).

winter conditions with an initial sea level temperature of 48° F. Lines 7 and 9 therefore represent the theoretical temperatures which would be attained by rising currents of moist air during the summer and winter respectively, and it is important to note how closely the actual observed data correspond with the theoretical condition. The lines 8 and 10, showing the theoretical adiabatic gradient for dry air show the temperature gradient which would be approximated by de-

scending currents of air from which the moisture has been partially removed by the low temperatures of the higher altitudes.

It should here be noted that if the air from an altitude of 30,000 feet were to descend to the sea level without radiation, the temperature would be raised by compression to about 136° F. in summer and to 82° F. in winter, on the basis of these adiabatic gradients. The radiation is so great, however, that the descending currents from

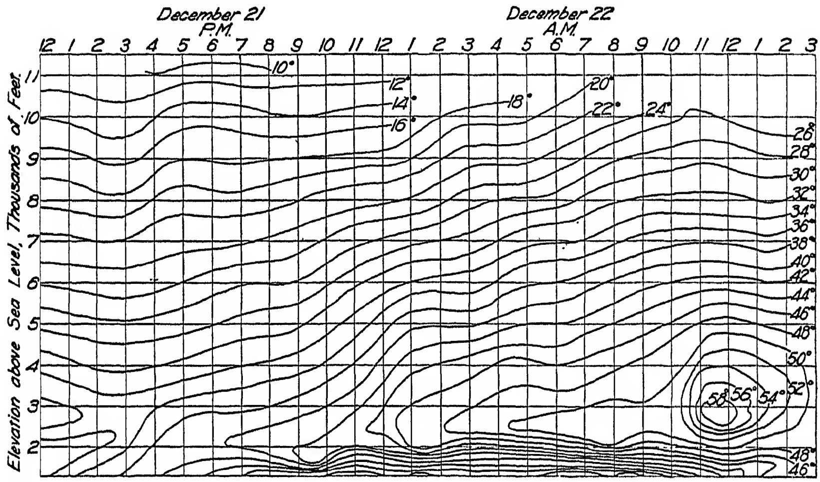

Fig. 61.—Free Air Temperatures in Degrees Fahrenheit above Drexel, Nebraska[5] (see page 114).

higher altitudes are usually much lower than air temperatures at the surface, as is evident whenever a high barometric condition prevails.

As might reasonably be expected, the mean annual temperature for any locality will decrease with the altitude and in approximate proportion to the temperature gradient for saturated air. Fig. 63 shows the theoretical temperature gradients for saturated air from a summer sea level temperature of 68° (A) and a winter sea level temperature of 48° (B), also the mean annual temperature gradients for closely adjoining stations in Colorado, California, New England and the European Alps, and the approximate agreement of the actual temperature gradients of the mean annual temperatures with the theoretical temperature gradients is shown.

From Sec. 59 it is evident that on account of the lower temperature of the higher altitudes, the vapor tensions and the consequent vapor content of the air must decrease rapidly with the altitude. That the

[5] Monthly Weather Rev. Sup. No. 3, 1916, p. 36.

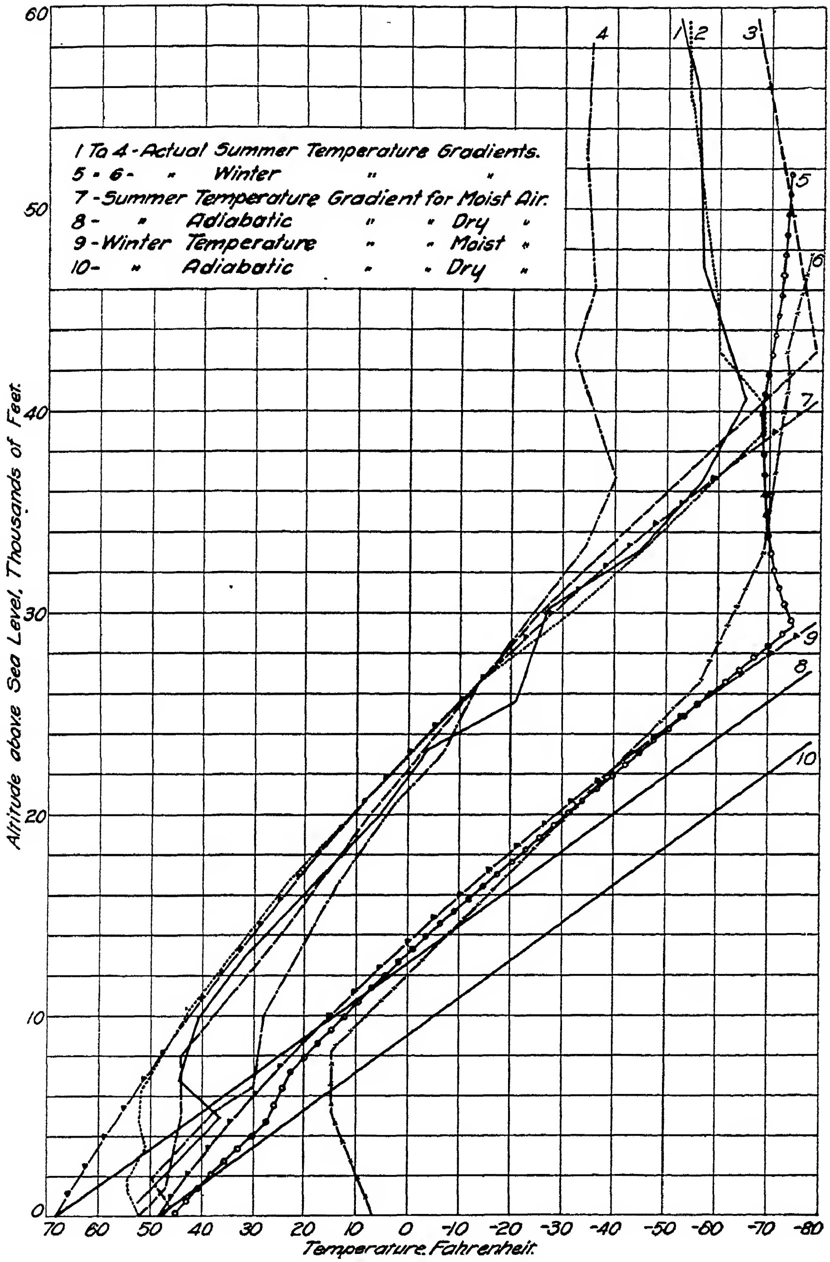

FIG. 62.—Vertical Temperature Gradients in Free Air (see page 114).

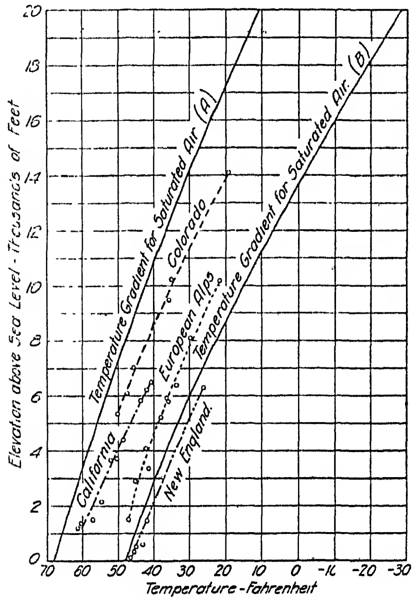

Fig. 63.—Theoretical Temperature Gradient and Decrease in Mean Annual Temperature with Altitude (see page 116).

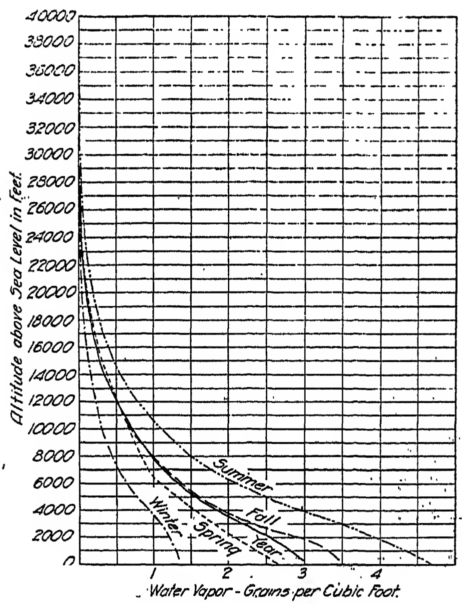

Fig. 64.—Vertical Distribution of Water Vapor on Clear Days (see page 119).

facts agree with the theory is made evident by Fig. 64,[6] where the actual vertical distribution of vapor for various seasons of the year is shown.

The quantity of vapor in the atmosphere decreases with the increase in altitude more rapidly than the pressure decreases, as will be seen by reference to Fig. 65, in which the decrease in vapor tension and

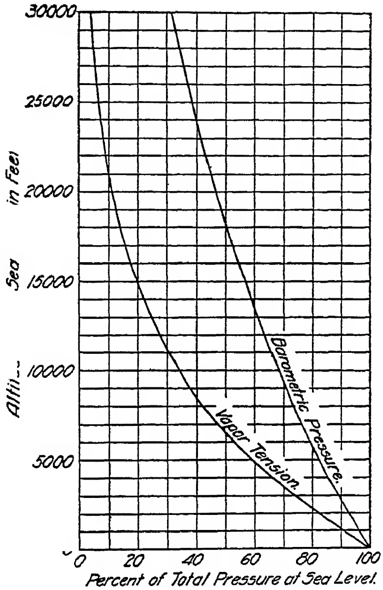

FIG. 65.—Decrease of Vapor Tension and Pressure with Increase in Altitude.

in atmospheric pressure is given in percentages of such tension and pressure at sea level.[7]

Vapor tension is practically proportional to quantity of vapor, hence the diagram shows the relative vapor content of the atmosphere at different elevations. About one-half the total moisture is contained in the atmosphere below an elevation of 6,500 feet, about three-quarters below 13,000 feet, and about nine-tenths below 21,000 feet. Hence on a clear day in winter with an absolute humidity of one grain per cubic foot at the surface of the earth, the total moisture in the atmosphere distributed over the surface of the earth would equal about .25 inches; while in summer with six grains of moisture per cubic foot at the sur-

[6] See Bulletin Mt. Weather Observatory, Vol. 4, part 3, 1911, p. 128.

[7] See Handbook of Climatology by Dr. Julius Hann. Translated by Prof. R. De C. Ward, 1903, p. 286.

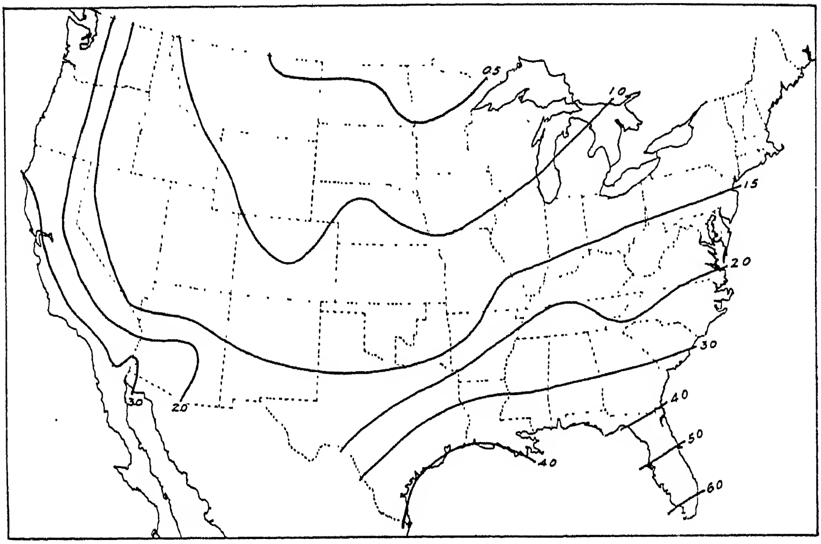

Fig. 66.—Average Distribution of Atmospheric Moisture in the United States for January. (Grains of water per cubic foot of air) (see page 121).

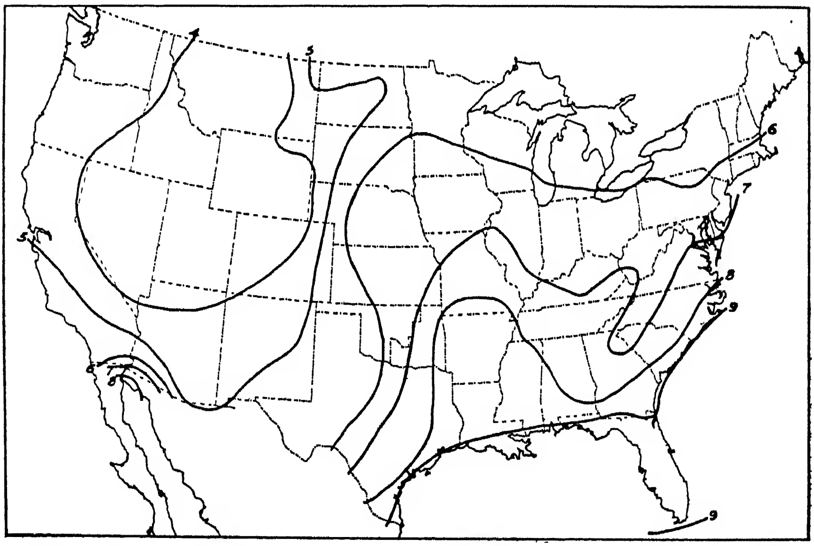

Fig. 67.—Average Distribution of Atmospheric Moisture in the United States for July. (Grains of water per cubic foot of air) (see page 121).

face, the total atmospheric moisture if so distributed would equal about 1.5 inches.

63. Geographical Distribution of Normal Atmospheric Moisture.—The moisture of the atmosphere is the result of vaporization from water surfaces, from vegetation and from other moist surfaces and is therefore usually found in greater absolute and relative quantities near the sources from which the moisture may be derived. On

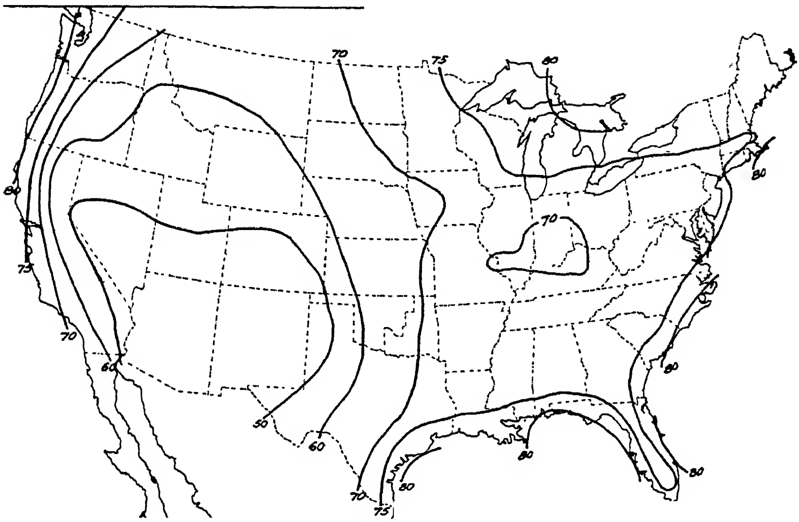

Fig. 68.—Average Annual Relative Humidity in the United States (percentage).

the ocean in the Doldrums the air is always near saturation. This is due to the Trade Winds which, flowing over the warm surfaces of the ocean with slowly rising temperatures as they advance, are continually supplied with vapor and maintained in an almost saturated condition. Over the deserts where the supply of moisture is very small the quantity of vapor in the atmosphere is far below its capacity. In general, the amount of moisture decreases toward the center of a continent, but this is modified by normal rainfall conditions, by the presence of large lakes, extensive forests and swamps and by prevailing wind movements.

The average distribution of atmospheric moisture in the United States in January and July is shown in Figs. 66 and 67 respectively, page 120, and the average annual relative humidity in the United States in terms of percentage of saturation is shown by Fig. 68.

64. **Variation in Absolute and Relative Humidity.**—Absolute humidity will vary at every locality from hour to hour and from day to day with atmospheric temperature, pressure, wind movement and resulting evaporation. Relative humidity will vary to a still greater extent, as with the same moisture content the degree of saturation will vary with the hourly variations in temperature. Both absolute and relative humidity will vary in still greater degree in different localities. The variation in temperature and both relative and absolute humidity from hour to hour at Madison, Wisconsin, for the period August 1 to 6, 1916, are shown in Fig. 69, page 122. The amount of precipitation during this period and the consequent changes in atmospheric moisture during this period are of interest. The variation in absolute humidity from month to month at various typical stations in the United States is shown in Figs. 70 and 71, page 123.

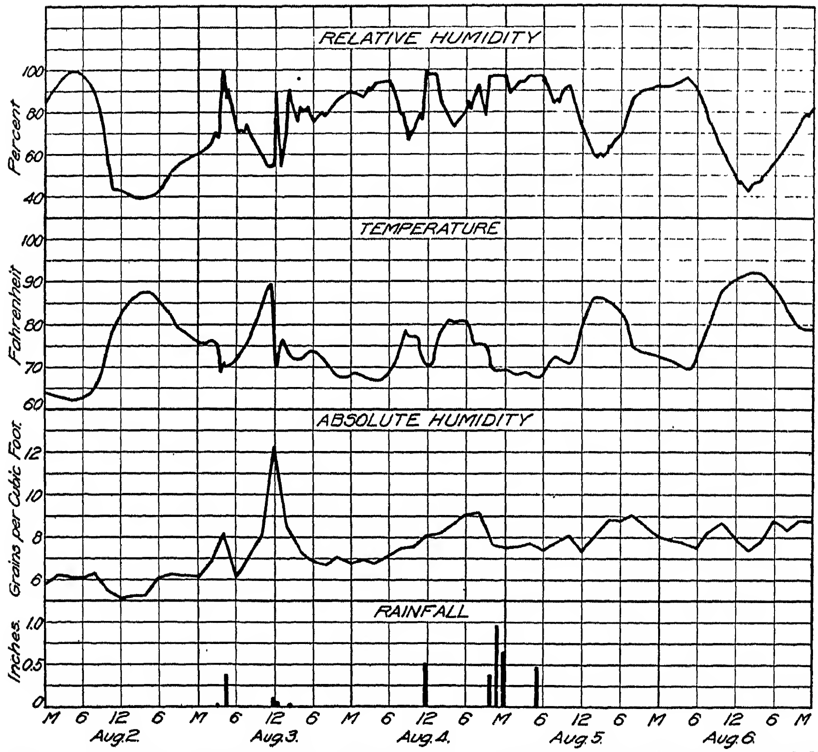

Fig. 69.—Relative Humidity, Temperature, Absolute Humidity and Rainfall from Midnight, August 1 to Midnight, August 6, 1916, at Madison, Wis.*

* Compiled from data furnished by E. R. Miller, U. S. W. B.

65. Interchange of Moisture Between Air and Land or Water Surface.—The moisture of the atmosphere is furnished by evaporation from water surfaces which cover nearly three-fourths of the earth's surface. The oceans, lakes, swamps and river surfaces, therefore, furnish the largest portion of atmospheric moisture. Additional sources are the ground surface, which is usually somewhat moist, and the transpiration of plants and animals. Vegetation through its roots, which often penetrate the soil to considerable depths, draws from the ground storage moisture which would otherwise remain as ground water. It is apparent that the wind will carry some of the vapor from

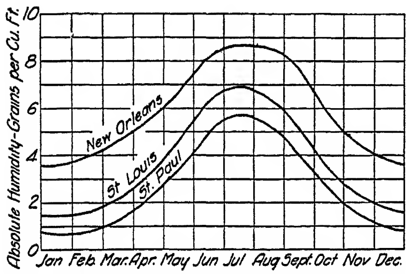

Fig. 70.—Variations in Average Absolute Humidity at Various Stations (see page 122).

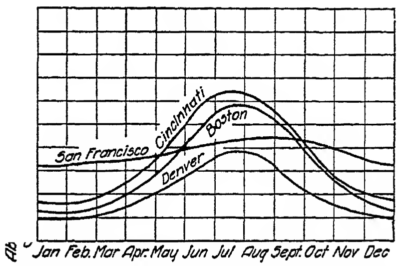

Fig. 71.—Variation in Average Absolute Humidity at Various Stations (see page 122).

the continent to the sea and some of the vapor from the ocean to the adjacent continents. Bruckner[8] has estimated that the net results of this interchange of vapor between the oceans and land is that only seven per cent. of the precipitation of the land comes from moisture received directly from the sea. The author believes, however, that this estimate is too small. The moisture of the air over continental areas is most largely drawn from the inter-continental water surfaces of lakes, swamps, marshes and streams, from moist earth areas and from the transpiration of forests and other vegetation and probably does not receive more than from twenty-five per cent. to thirty-five per cent. from the oceans. (See Table 13, page 165.)

Evaporation is continually taking place from a moist surface whenever the water is above the dew point temperature of the air which is in contact with it. Whenever the water or other surface in contact with moist atmosphere falls in temperature so that the air in contact is reduced in temperature below the dew point, condensation occurs and dew is formed on the exposed surface. There is therefore a con-

[8] The Relation of Forests in the Atlantic Plain to the Humidity of the Central States and Prairie Regions, by Dr. Raphael Zon. Science, Vol. 38, p. 69.

stant exchange of moisture between the air and moist surface, sometimes by evaporation from the water to vapor and sometimes by condensation from vapor to moisture. The observed evaporation from water surfaces is the net result of this interchange of moisture.

66. Heat Changes Involved in Evaporation and Condensation.—As water increases in temperature it must absorb heat, as in the case

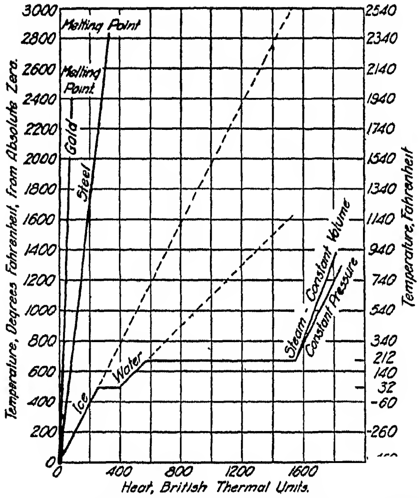

FIG. 72.—Relations of Heat Energy in Water.*

of all other bodies. When however water changes its physical form from solid (ice) to liquid (water) or from liquid to vapor, a large amount of heat is absorbed and becomes latent. The heat necessary for the increase in temperature through a wide range is shown by Fig. 72, page 124. In this diagram the amount of heat required to raise the temperature of water is compared with the amount of heat necessary to raise the temperature and to melt gold and steel. The latent heat of melted ice and of vaporized water, which is not manifest by an increase in temperature, is shown by the horizontal lines of the diagram.

From this diagram it becomes evident that when water is evaporated, a considerable amount of energy must be absorbed from some source. This energy may be obtained by the reduction of temperature in the water itself or of the body in which it is contained or by radiant energy from the sun or from adjacent bodies. In the same manner condensation is accompanied by a transformation of latent to percep-

* Lecture by G. H. Babcock. Sci. Am. Sup. Dec., 1887.

tible heat which is delivered to the atmosphere and has an important effect on the dynamics of storms.

Dew and frost are caused by the radiation of heat from the earth's surface into a clear atmosphere, the reduction in the temperature of the adjoining air below the dew point, and consequent condensation. Low fogs are the result of a similar radiation and reduction of tem-

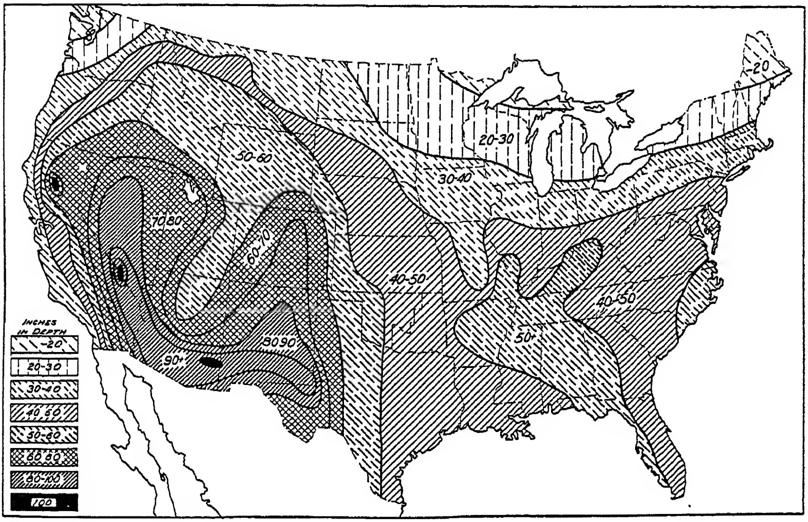

Fig. 73—Relative Annual Evaporation from Free Water Surfaces in the United States.

perature in the lower atmosphere. High fogs and clouds are the result of dynamic cooling due to expansion of rising vapors. The condensed particles of moisture which make up clouds and fogs are very small, varying from .001 to .00025 inch in diameter, and they are maintained in suspension in the atmosphere by ascending air currents. As a drop of water .001 inch in diameter would fall at the rate of less than two inches, per second,[9] it requires a feeble upward current to maintain it in suspension.

67. **Evaporation.**—Evaporation takes place from moist surfaces and from the water surfaces whenever such surfaces are in contact with unsaturated air. Fig. 73, is a map showing roughly the annual evaporation which takes place from water surfaces at various points within the United States. This map and the table of monthly evaporation in the Appendix are taken from data given in the Monthly

[9] See Meteorology, by W. I. Milham, 1912, p. 232.

Weather Review of September, 1888. The Weather Review observations were deduced from readings of dry and wet bulb thermometers as observed at various signal Service Stations in 1887 and 1888. These deductions were supplemented by observations at several stations by means of the Piche evaporimeter. This map (Fig. 73) shows the annual evaporation rates in the greater portion of the United States to be equal to or greater than the local annual rainfall. The total annual evaporation as shown by the map is, however, based on free water surfaces only, and evaporation from ground surfaces takes place only from occasional moist surfaces which exist after rains.

While evaporation, like rainfall and other meteorological phenomena, varies from year to year in accordance with the variation in the controlling factors, yet this variation is apparently much less than the variation in most other meteorological phenomena such as rainfall, temperature, etc. This map and the table therefore indicate relative conditions at the various stations and roughly the evaporation from free water surfaces. The comparative monthly evaporations at sixteen stations distributed throughout the United States, and based on these tables, are shown graphically by Fig. 74. At a number of places in the United States evaporation observations have been made for a number of years and from the data thus collected a general knowledge of local variations that occur in evaporation can be obtained.[10] When the amount of evaporation becomes an important element in engineering problems, a study must be made in detail of the local conditions which modify its distribution and total amount.

68. Factors of Evaporation.—Evaporation at any time or place will depend on various physical and meteorological conditions most of which will vary from time to time. The meteorological conditions frequently vary with considerable rapidity from hour to hour (see Figs. 21, 32 and 69). The principal meteorological factors are: vapor tension, temperature and wind movements in which the variations are considerable and cannot be forecast with any degree of certainty, except as to monthly average which can be foretold only within certain rather definite limits. In consequence these factors must be considered broadly for practical purposes.

The physical factors to be considered are: altitude and nature of the surface from which evaporation occurs, and the subsurface so far as it affects the amount of evaporation. In general, the surface conditions may broadly be divided into land and water surfaces.

[10] See Literature at end of chapter.

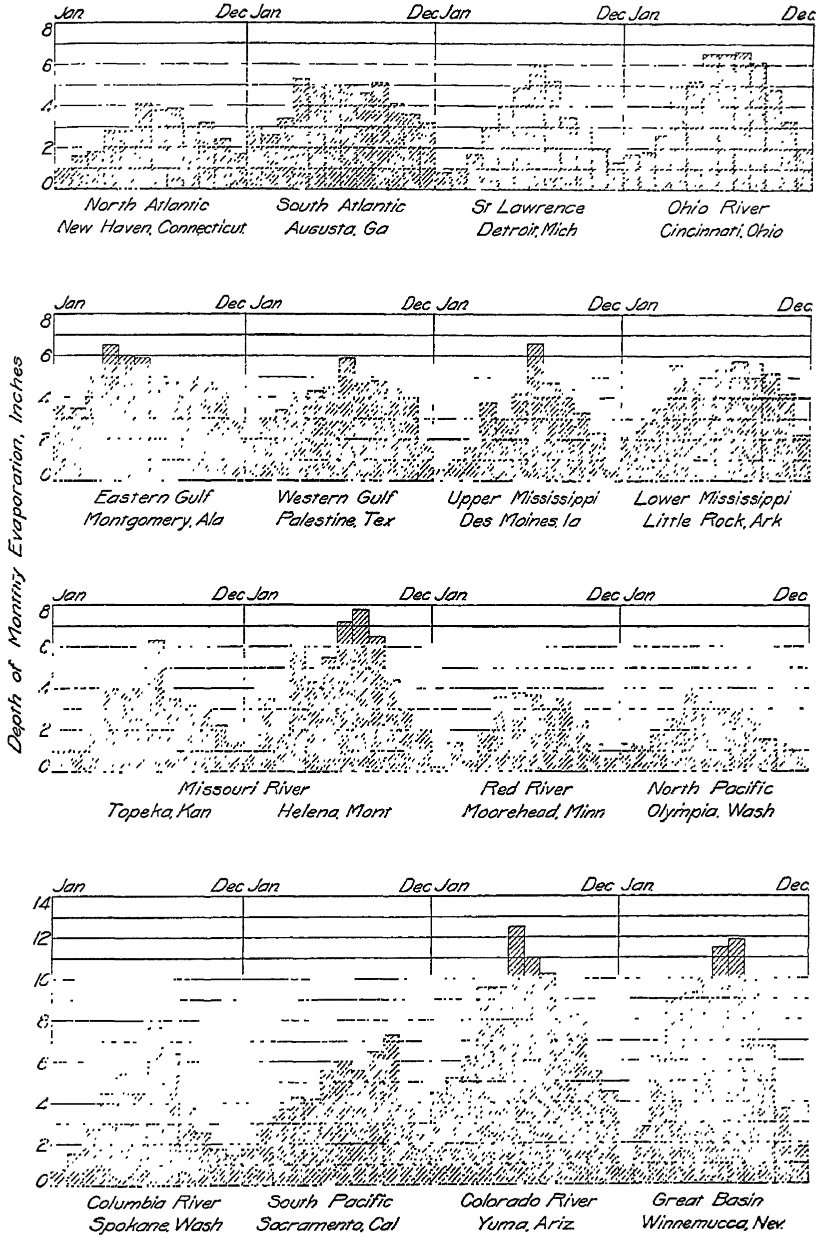

FIG. 74.—Monthly Evaporation from Free Water Surface at Sixteen Stations in the United States (see page 126).

The body of water from which evaporation takes place may be small or large, exposed or protected from the wind, it may be shallow or deep, it may be free or filled with more or less vegetation. If exposed to wind movements, if small, shallow or filled with vegetable growth, evaporation will be increased. In the summer when evaporation is at a maximum more water will evaporate from small and shallow bodies than from deep and large bodies on account of the increased temperature in the small bodies of water. The presence of vegetation will also add to the amount of water loss as evaporation will be augmented by the transpiration of the growing plants. Evaporation from ice surfaces while comparatively small is still a factor not to be ignored.

The evaporation from land surface normally depends upon the amount, intensity and distribution of the rainfall and also on the moisture conditions of the surface. Light rains may be evaporated from the surface while much of a heavy rainfall will percolate into porous soil beyond the reach of evaporating influences. Land surfaces may be saturated, moist, dry, frozen or covered with snow or ice. They may be of loam, sand, clay or rock of varying characters and underlaid with various materials in endless varieties and of varying porosities. The surface may also be bare or cultivated; it may be covered with crops of various characters; it may be grass land or forests. The exposure to winds is also important.

It is evident that comparatively more evaporation will take place from wet than from dry land and that in the latter case no evaporation will take place unless the capillarity of the soil or the roots of plants draw the water from lower levels.

It is apparent therefore that the whole question of evaporation from any drainage area is a very complicated subject that can be ascertained with no great degree of accuracy but which nevertheless must be investigated and understood so far as practicable in order that many important problems of hydraulic engineering may be solved with as great a degree of certainty as the conditions permit.

69. **Vapor Tension.**—The rate of evaporation at any time depends not on the relative humidity which varies rapidly with atmospheric temperature, but on the vapor tension due to the temperature of the water surface (V) and the vapor tension in the layer of air in contact with the water surface (v). If this difference be large, evaporation will be rapid, while evaporation will decrease with the difference and will change to condensation when this difference is negative (see Fig. 75, page 129).

Just how these vapor tensions should enter into a correct formula for evaporation has not yet been accurately determined, although a number of such formulas have been proposed. The experiments of

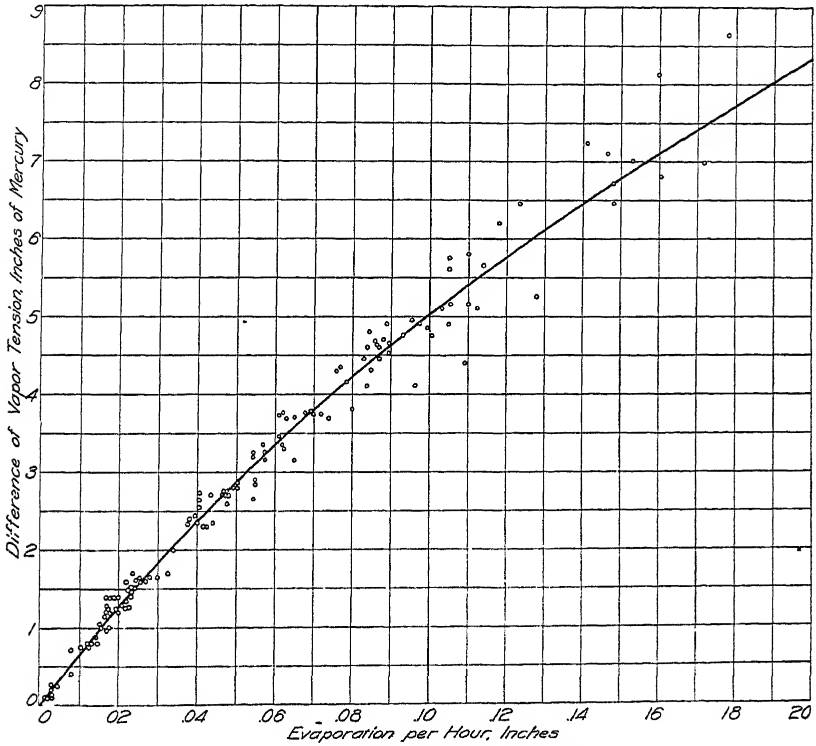

FIG. 75.—Effect of Vapor Tension on Evaporation.

Mr. Desmond Fitzgerald, made in the city of Boston show that evaporation (e) varies in accordance with formula (2).[11]

$$(2) \qquad e = .014\ (V - v) + .0012\ (V - v)^2$$

This formula was determined from experiments platted in Figure 75. Other experiments seem to indicate, however, that the formula is not of general application even when corrected for wind, altitude, etc.[12]

[11] See Evaporation, by Desmond Fitzgerald. Trans. Am. Soc. C. E., Vol. 15, p. 581 *et seq;* also studies of evaporation, by Prof. F. H. Bigelow, U. S. Weather Review, Vol. 35, p. 311 (in which various formulas are compared).

[12] See Studies of the Phenomena of the Evaporation of Water over Lakes and Reservoirs, by Prof. F. W. Bigelow. Monthly Weather Review, July 1907, p. 311.

70. **Temperatures.**—These vapor tensions depend on the temperatures of the water and the dew point temperature of the air, both of which vary continually and therefore cannot be of general value (even were their relations definitely established) for estimating monthly or annual evaporation in which the engineer is more directly interested, although they may prove important as a means for detailed investigations.

Some of the comparative variations in air, water and earth temperatures have already been shown in Fig. 14, page 48. Similar tempera-

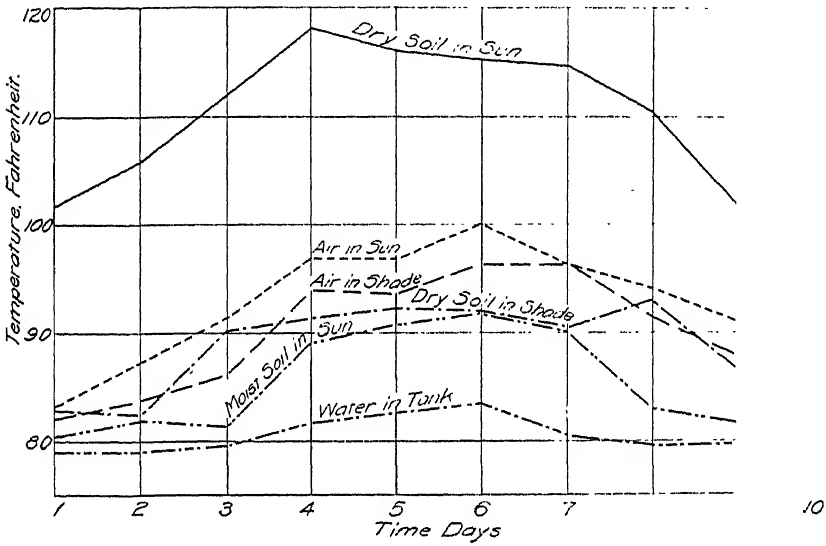

Fig. 76.—Average Daily Temperatures for Ten Consecutive Days, beginning August 24, 1905, at Arlington Heights.

ture variations relative to exposure in sun and shade and between moist and dry soils are shown in Fig. 76.[13]

The waters of lakes, reservoirs and canals, in which the determination of the amount of evaporation becomes of importance to the engineer, are in general exposed to the sun and weather, and while their temperatures do not vary hourly and daily directly with the temperature of the air, there is a more direct relation between the average monthly temperature of air and water in any locality.

The investigations of Dr. Fortier[14] do not indicate any constant re-

[13] Bulletin 177 U. S. Dept. Agriculture, Evaporation Losses in Irrigation, by Dr. Samuel Fortier, p. 42, Fig. 17.

[14] *Ibid.*

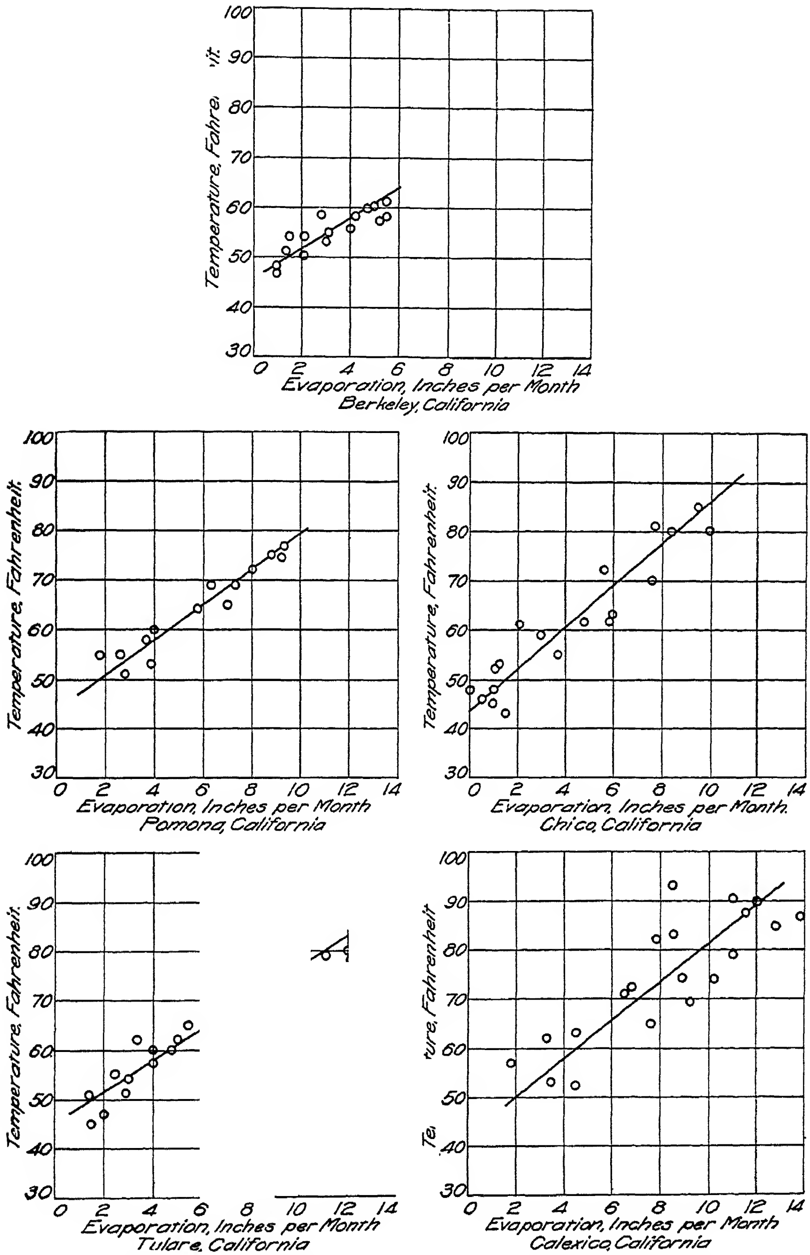

FIG. 77.—Relation of Evaporation to Temperature at Various Stations (see page 132).

lation between temperature and evaporation, although in general increased temperature results in increased evaporation. (See Fig. 77, page 131).

Fig. 77 and some of the following diagrams seem to indicate that no evaporation would take place below certain temperatures, which vary more or less in each particular case. This indication is undoubtedly erroneous as evaporation will occur even from the surface of snow and ice with other conditions favorable, hence these lines cannot be straight as the diagrams in general indicate.

Mean atmospheric temperatures are the data most widely available, and it is important that such data be utilized if possible as one of the factors for the practical estimation of evaporation. That there is a fairly close relation between mean monthly temperatures and mean monthly evaporations for any given locality has been demonstrated by many evaporation experiments. The experiments by Fitzgerald demonstrate such a relation. (See Fig. 78, page 134.) General average relations determined by various experiments are shown in Fig. 79,[15] page 135, from which it will be seen that while such a relation seems to be fairly constant for any given locality, other factors so modify the results that the relation cannot be applied in any general way without at least taking into account other modifying factors. Such factors from previous consideration must evidently include at least altitude and wind velocity.

71. **Wind Movements.**—Evaporation is greatly promoted by atmospheric currents which have perhaps the most marked effect of any single influence. A brisk wind will rapidly remove the air which is in contact with the water or moist surface and more or less nearly saturated, and substitute dry air or air which is of lower humidity. The vapor which results from evaporation will, in the absence of wind, hang like a blanket over the water surface, and by reducing the difference in vapor tension (V—v), materially reduce evaporation. A slight breeze will quickly remove the vapor blanket over an evaporation pan, thus greatly facilitating evaporation; while in large lakes and reservoirs the evaporation will be hastened on the windward side but will decrease on the other side, thus effectively reducing the evaporation of the larger body of water below that indicated by the evaporation pan.

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[15] A study of the Depth of Annual Evaporation from Lake Conchos, Mexico, by Edwin Duryea and H. L. Haehl. Trans. Am. Soc. C. E., Vol. 80, 1916, p. 1829 *et seq.* See also Evaporation, by Desmond Fitzgerald.

Dr. Fortier[16] found that the daily evaporation from pans increased from .07 to .85, or an average of forty-six per cent. per mile of wind movement, while Fitzgerald found the increase to be $1 + .013$, and Carpenter[17] found the increase to be $1 + .0015w$, in which $w =$ wind movement in miles per hour. As in general the velocity of the wind increases with altitude, this may account for the very rapid increase in evaporation with altitude and temperature, shown in Fig. 81. Wind movements as recorded at Weather Bureau Stations are of little value for the determination of evaporation from water surfaces, as the point of observation is usually at a considerable elevation and the records give little information as to the actual air movement closely adjoining the water surface. Fitzgerald found that at Boston the air movement at the surfaces was about one-third of the movement recorded on a 30 foot tower.

The velocity of the wind decreases rapidly as the surface of the earth is approached. Biglow found at India by placing one anemometer 10 feet above the evaporation pan and another anemometer at the elevation of the pan, that usually the lower anemometer recorded from 30 to 50 per cent. less wind movement than the upper one. He therefore concluded that "every pan must invariably be supplied with its own anemometer whenever evaporation observations are made on land or on large bodies of water." He also concludes that wind effects equal $1 + .043w$.[18] This is three and one-half times that used by Fitzgerald and thirty times that used by Carpenter.

72. **Effect of Altitude on Factors of Evaporation.**—A reduction in atmospheric pressure increases evaporation when wind movements, temperature and relative humidity remain the same. On this account, other things being equal, evaporation is greater in the mountains than in the lowlands. This is shown by the fact that the temperatures of vaporization (the boiling point) is greatly reduced at increased altitudes. This critical temperature is reduced 19° F. between sea level and an altitude of 10,000 feet. The reduction in boiling point due to altitude is shown in detail in Table 6. Temperature, however, which so greatly affects evaporation, decreases so much more rapidly than pressure that the actual evaporation at high altitudes is in general less than on the low lands in the immediate vicinity (see Fig. 80, page 136).

Duryea and Haehl have apparently determined fairly constant re-

16 See Bulletin 177, U. S. Dept. of Agriculture, p. 45.
17 Weather Review, July, 1907.
18 Weather Review, Feb. 1910.

TABLE 6.

Boiling-Point of Water Corresponding to Barometric Pressure and Altitude Above the Sea-Level.

Boiling-point		Barometer		Altitude Feet	Boiling-point		Barometer		Altitude Feet
F°	C°	Inches	mm.		F°	C°	Inches	mm.	
184	84.4	16.79	426.5	15221	200	93.3	23.59	599.2	6304
185	85.0	17.16	436.0	14649	201	93.8	24.08	611.6	5764
186	85.5	17.54	445.5	14071	202	94.0	24.58	624.3	5225
187	86.1	17.92	455.4	13498	203	95.0	25.08	637.0	4697
188	86.6	18.32	465.3	12934	204	95.5	25.59	650.0	4169
189	87.2	18.72	475.6	12367	205	96.1	26.11	663.2	3642
190	87.7	79.13	486.0	11799	206	96.6	26.64	676.7	3115
191	88.3	19.54	496.3	11243	207	97.2	27.18	690.4	2589
192	88.8	19.96	507.0	10685	208	97.7	27.73	704.3	2063
193	89.4	20.39	517.9	10127	209	98.3	28.29	718.6	1539
194	90.0	20.82	528.8	9579	210	98.8	28.85	752.8	1025
195	90.5	21.27	540.0	9031	211	99.4	29.42	747.3	512
196	91.1	21.71	551.3	8481	211	100.0	30.0	762.0	sea
197	91.6	22.17	563.4	7932	below	sea	level		level
198	92.2	22.64	575.0	7381	213	100.5	30.59	777.0	512
199	92.7	23.11	587.0	6841					

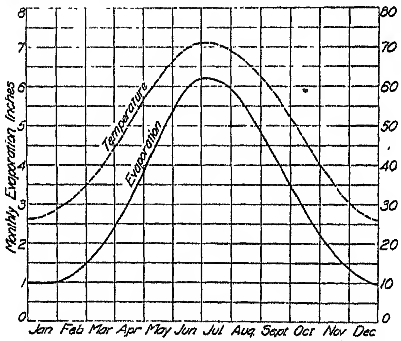

Fig. 78.—Relation of Evaporation and Temperature at Boston, Mass. (see page 132).

lations for altitude, temperature and evaporation among certain stations in the southwest portion of the United States. From these investigations Fig. 81,[19] page 136, has been made. The data used by Duryea and Haehl are more or less indefinite and imperfect. This is especially true of the data for Carlsbad which are averages of two stations, the data from both of which are believed to be in error. Their conclusions are intended to apply only to the region of the Great Plateau from Mexico north to Colorado and Utah.

[19] Evaporation from Lake Conchos, Duryea and Haehl.

While the relations shown in Fig. 81, between the stations at Albuquerque, Elephant Butte, Carlsbad and Austin seem fairly consistent, similar data shown on this diagram for El Paso, which is in the same district, are discordant and it would seem that the relations indicated are more a matter of chance than of law. Similar data for Boston, Mass., Columbus, Ohio and Menasha, Wisconsin are still more discordant and indicate that even if this diagram fairly represents a local relation, it cannot be regarded as general.

In general it is held that with temperature, wind movements and relative humidity equal, evaporation will be inversely proportional to

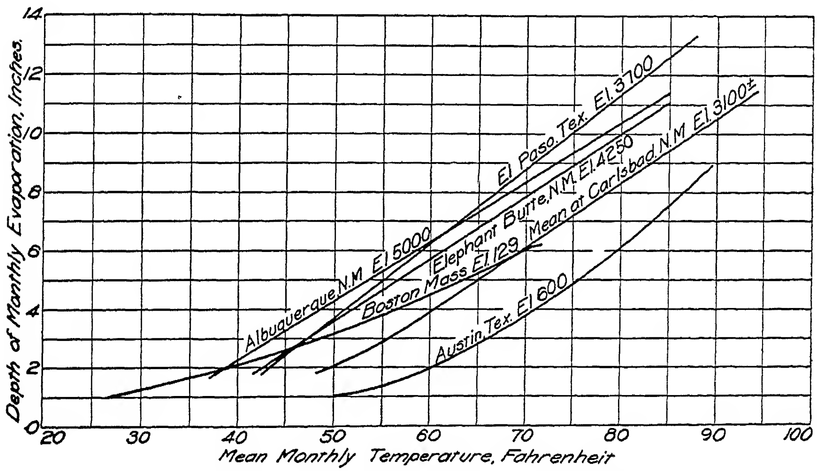

Fig. 79.—Relations between Mean Evaporation and Temperature at Various Stations (see page 132).

atmospheric pressure; hence at a given temperature evaporation should increase directly with the reduction in barometric pressure, due to altitude.

In Fig. 82, page 137, the theoretical evaporation at various elevations is shown relative to sea level under similar conditions of (mean monthly) temperature, wind and humidity, in accordance with the above law. On this diagram is platted the increase in evaporation with altitude and constant temperature of the station previously considered in Fig. 81. The discordant results indicate that the wind movements or relative humidity at the higher altitudes have had a decided accelerating effect on evaporation.

73. Evaporation of Snow and Ice.—Snow and ice exposed to atmospheric agencies decrease in volume by sublimation due to the same

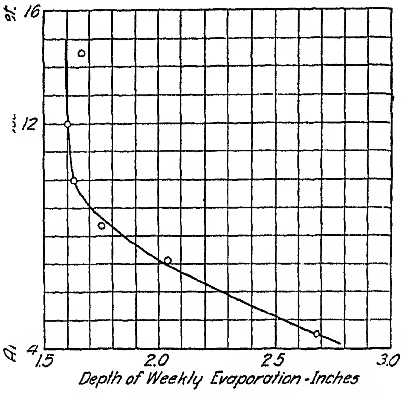

Fig. 80.—Influence of Altitude on Evaporation on Eastern Slope of Mount Whitney, Cal. (see page 133).

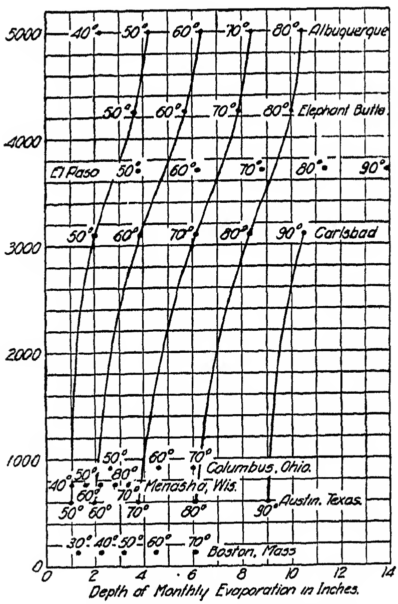

Fig. 81.—Relations between Evaporation and Temperature at Various Altitudes (see page 134).

factors which cause evaporation from moist land and water surfaces. With the thermometer below the freezing temperature, the wind is apparently the greatest factor in this phenomena. The information on this subject is fragmentary and the loss difficult to determine on account

of varying conditions even within limited areas. Fitzgerald[20] found that average evaporation from snow was 6 inches per month and concluded that evaporation from ice is nearly twice as rapid as from snow, and might equal six inches per month with a 12-mile wind. Lee[20] estimated the loss from snow field on the highest mountain areas (the Sierra Nevadas) at 7.7 inches (of water) per season. Lippincott[21] estimated the season's loss on the high mountains of the San Bernardino Valley at 14 inches of water. Baker[22] made various experiments at

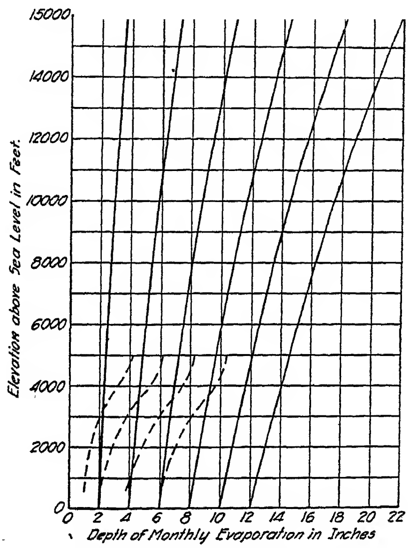

FIG. 82.—Relations between Evaporation and Pressure (see page 135).

the Utah Experimental Station which are shown relative to the simultaneous temperature in Fig. 83, page 138 on which are also plotted Lippincott's observations, all reduced to monthly rates of evaporation. The wide departure from a curve drawn through the centers of gravity of the various groups of ten points shows the influences of wind, vapor tension, etc.

The effect of forests in decreasing sublimation seems largely to be

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20 Evaporation, by Desmond Fitzgerald. Trans. Am. Soc. C. E., Vol. 15, p. 610. Water Resources of a part of Owens Valley, Cal., by Chas. L. Lee, Water Supply Paper No. 294, p. 50.

21 Water Supply of San Bernardino Valley, by J. B. Lippincott, Nineteenth Annual Rept. U. S. G. S. Part 4, p. 624.

22 Some Field Experiments on Evaporation from Snow Surfaces, by F. S. Baker. Mon. Weath. Rev. July, 1917, p. 363.

due to their influence in checking wind velocity, thus affecting drifting and erosion, and in shading thus diminishing the direct insolation. On the other hand these effects may be offset, particularly in the case of coniferous forests, by the lodgment of snow on the trees themselves

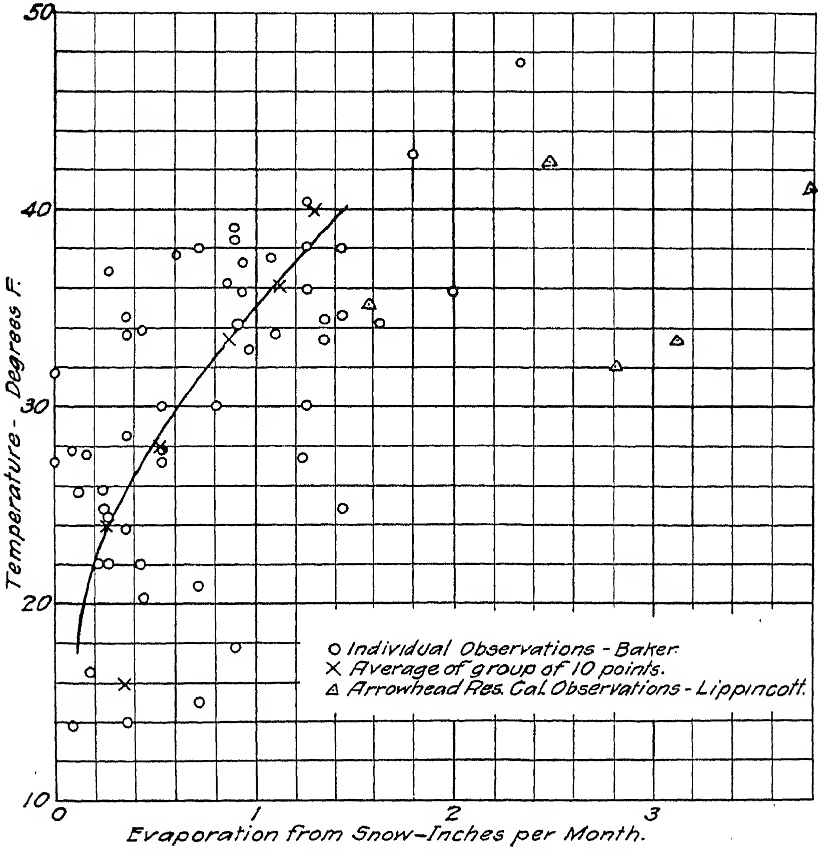

FIG. 83.—Observations of Evaporation from Snow.

which increases the area exposed to evaporative action. This subject becomes of special importance in connection with the study of the relation of mountain snowfall to water supply for cities, irrigation and water power.

74. **Evaporation From Land.**—The character and depth of the soil or other surface material, the condition of the surface, whether bare, cultivated or with vegetation, its composition and underdrainage as well as the various factors hitherto discussed, all have important influences on the amount of evaporation from the land.

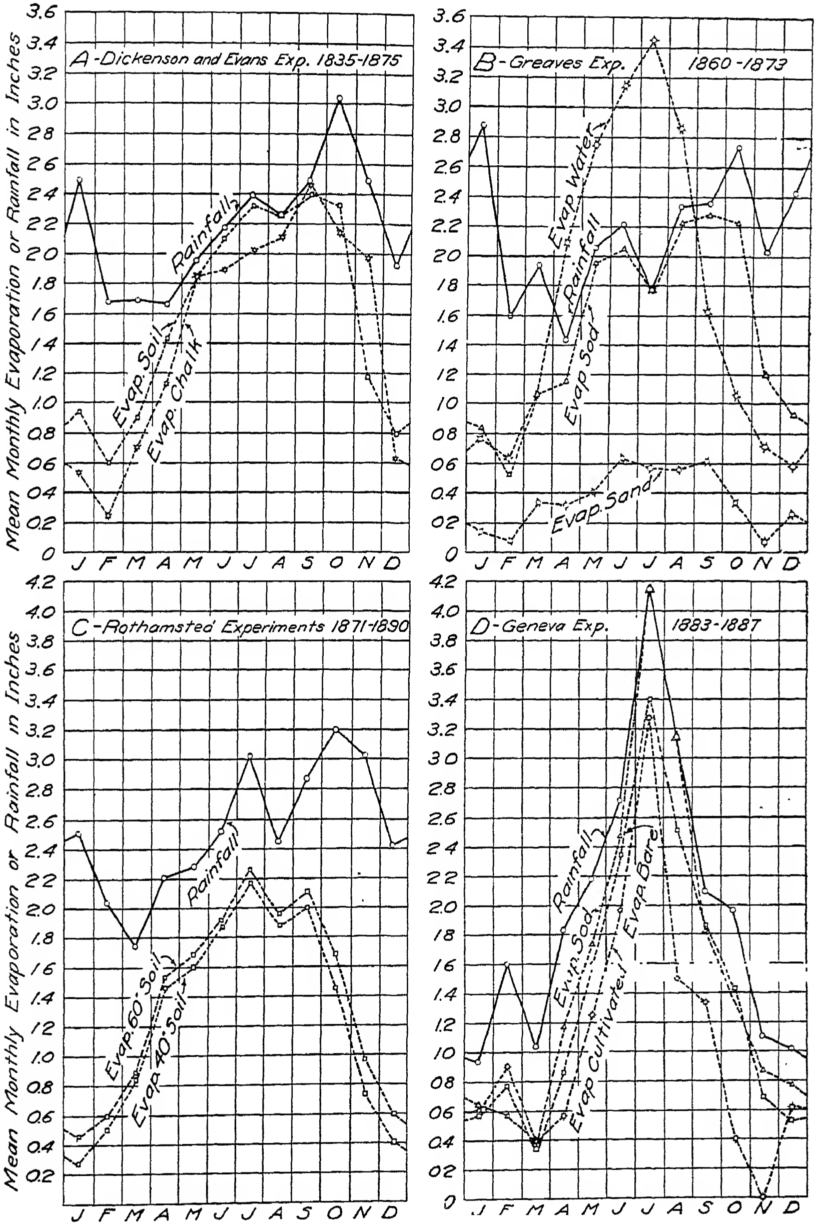

FIG. 84.—Evaporation from Soils (see page 141).

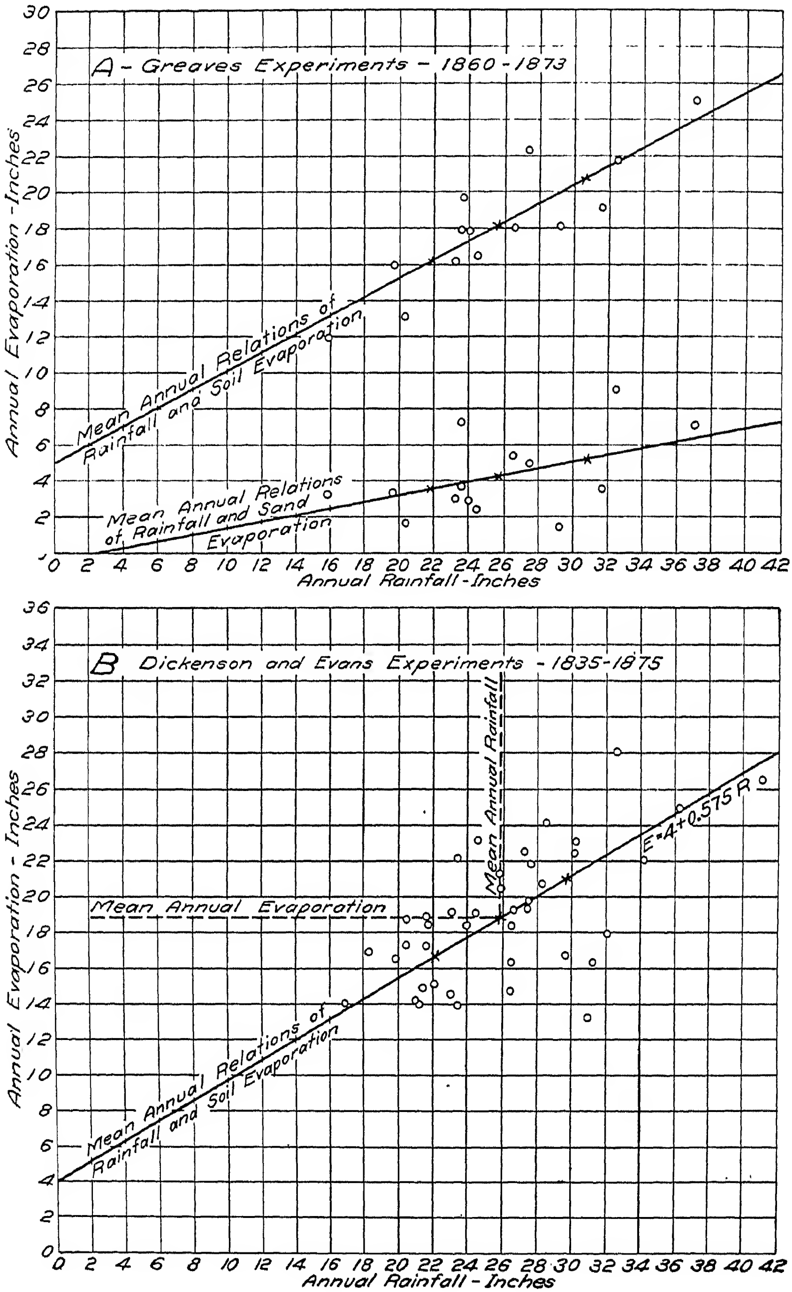

FIG. 85.—Relations between Rainfall and Evaporation (see page 141).

The various experiments on soil evaporation made in the past are all subject to various experimental errors but these errors are much less in magnitude than the differences that will occur with various conditions of soil, so that they may all be regarded as fairly illustrative of the various divergences which will be found to exist in different locations often on the same drainage area. In all of these experiments the annual rainfall was measured and compared with the amount of water which percolates through the soil. The difference between these two quantities was estimated as soil evaporation. In some cases different soils were compared with each other and with the water evaporating from free water surfaces, and in one case also from a shaded water surface. The average results of each series of experiments are shown in Table 7. Fig. 84, page 139, shows the relative rainfall and evaporation as determined from experiments: (A) by Dickinson and Evans at Hertsfordshire, England (1835–1875); (B) by Charles Greaves at Lee Bridge, England (1860–1875); (C) by Gilbert and Lawes at Rothamsted, England (1871–1890); and (D) by the Geneva (N. Y.) Experimental Station (1883–1887). In these diagrams should be noted the differences in evaporation between a free water surface, grass covered soil and sand (B), the increased evaporation from soil 60″ deep as compared with soil 40″ deep (C), and the difference in evaporation between grass covered soil, bare soil and bare cultivated soil (D).

The relations of annual rainfall to soil evaporation under various conditions are shown in Fig. 85, page 140. In each of these cases the annual rainfall is shown as abscissas and the corresponding evaporation by ordinates; and if the annual evaporation were constant and approximately equal to the average, they would fall approximately on a horizontal line. These experiments show by their greater approximation to the inclined lines, for each of which a mathematical expression (or formula) in terms of rainfall and evaporation can easily be derived (thus, the equation of the line A. B. (Diagram B) is $E = 4 + .575 R$) that in general soil evaporation increases with rainfall, which would normally be expected as the soil would as a rule be wet for a greater proportion of the time.*

*It should be noted that the extension of the line shows an evaporation of 4 inches with zero rainfall which is evidently incorrect. A curved line passing through the origin of co-ordinates and approximating the line through the centers of gravity would agree better with theoretical conditions.

TABLE 7— *Averages of Evaporation Experiments from Soil, etc.*

Authority	Locality	Character of Soil	Depth of Soil	Size of Gage	Duration of Experiment	Rain in.	Evaporation From Water in.	Evaporation From Soil In.	Percolation	Reference
Dalton	Manchester, Eng.	Local	3 ft.	10 in. diam.	3 yrs.	33.56	44.41[1]	25.15[3]	8.41	Beardsmore, p. 123
Charnock	Yorkshire, Eng	Local	3 ft.	10 in. diam.	5 yrs.	24.60	35.04[1]	19.82[3]	4.82	Beardsmore, p. 123
Charnock	Yorkshire, Eng	....	....	....	5 yrs.	24.00	23.55[2]	....	....	Beardsmore, p. 123
Ebermayer	Bavaria	Local	4 ft.	1 ft. sq.	1 yr.	36.00	....	16.6[3]	19.4	Proc. Inst. C. E. vol. 45. p. 57
Ebermayer	Bavaria	Local	4 ft.	1 ft. sq.	1 yr.	27.50	....	11.0[6]	16.5	Proc. Inst. C. E. vol. 45. p. 57
Maurice	Geneva	....	2 ft.	....	2 yrs.	26.0	....	15.8	10.2	Proc. Inst. C. E. vol. 45, p. 56, Bibl. Univ. de Geneve, Sciences et Arts. t. 1
Gasparin	S. France	....	2 ft.	....	2 yrs.	28.0	....	22.4	5.6	Proc. Inst. C. E. vol. 45, p. 56, Cours d' Agriculture. t. 11. p. 116
Risler	Caleves, Switz[4]	....	4 ft.	....	2 yrs.	41.0	....	28.7	12.3	Proc. Inst. C. E. Vol. 45. p. 56, Archives des Sciences de la Bib. Univ.. Sept.. 1869
Greaves	Lee Bridge, Eng	Sand	3 ft.	3 ft. sq.	14 yrs.	25.7	....	4.31	21.41	Proc. Inst. C. E. vol. 45, p. 30
Greaves	Lee Bridge, Eng	Local	3 ft.	3 ft. sq.	22 yrs.	25.8	....	18.97	6.87	Proc. Inst. C. E. vol. 45, p. 30
Dickenson and Evans	Hertfordshire, Eng.	Soil	3 ft.	3 ft. sq.	41 yrs.	26.0	....	18.91	7.09	Beardmore p. 124. Proc. Inst. C. E. vol. 20, p. 220 & vol. 45. p. 208
Dickenson and Evans	Hertfordshire, Eng.	Chalk	3 ft.	3 ft. sq.	22 yrs.	25.50	....	17.03	8.97	Proc. Inst. C. E. vol. 20, p. 222 and vol. 45. p. 208
Gilbert and Lawes	Rothamstead	Soil[5]	5 ft.	6 ft x 7¼ ft.	20 yrs.	30.29	....	16.68[3]	13.61	Proc. Inst. C. E. vol. 105, p. 35
Rafter	Geneva, N. Y.	Sod[5]	3 ft.	25 in. sq.	5 yrs.	23.75	....	19.86	3.87	New York State Museum, Bul. 85 p. 149
		Bare	3 ft.	25 in. sq.	5 yrs.	23.75	....	16.95	6.78	New York State Museum, Bul. 85, p. 149
		Cultivated	3 ft.	25 in. sq.	5 yrs.	23.75	....	12.79	11.49	New York State Museum, Bul. 85. p. 149

[1]Free water surface exposed. [2]Free water surface shaded. [3]Bare soil. [4]Drains under cropped field. [5]In place.
[6]In forest covered with forest litter.

Certain general conclusions concerning annual evaporation can be drawn from these experiments as follows:

1. Evaporation from soil increases with the rainfall.
2. Evaporation from soil is less than from free water surfaces.
3. Evaporation from sod is greater than from bare or cultivated soil.
4. Evaporation from cultivated soil (uncropped) is less than from bare soil.
5. Evaporation from deep soil is more than from shallow soil (both being underdrained).

It should be noted, however, that there is a considerable departure in various experiments from either a fixed average or from the relations expressed by the straight inclined lines, and that any attempt to calculate the annual soil evaporation from the annual rainfall would in general be subject to large errors. This variation is due to the variation in the distribution of rainfall, temperature, vapor tension, wind velocities and other factors which are unknown and which even if known for these experiments would be impossible of exact expression as a whole especially as regards distribution of rainfall and periods of frozen ground.

Certain important conditions not covered by the experiments previously discussed arise when land is without adequate drainage and the ground water is maintained at or near the surface by inflow from the surrounding drainage area, in the case of swamps, or from underground flows as in the case of various Western rivers in which there is no surface flow for considerable periods (as in the case of the Platte, Arkansas and Rio Grande Rivers). An important series of experiments were undertaken at the Denver Irrigation Field Laboratory in 1916 on evaporation from river bed materials under the conditions described above.[23] In these experiments which extended over a three-month period the various materials were placed in tanks two feet in diameter and the water maintained at certain fixed distances below the surface. The resulting evaporation from the tanks was compared with the evaporation from a free water surface in a similar tank containing a depth of 3 feet of water. This comparison seems to give the experiment a wider significance than otherwise would be the case. On account of the limited funds available, more extended experiments were made on laboratory soil

[23] See "Evaporation from the Surface of Water and River Bed Materials," R. B. Sleight, Jour. Agric. Research, Vol. X., No. 5.

and on Cherry Creek sand than on the other river bed materials, and as the results seem entirely consistent the probable results under other relations of saturation of the river bed material can be judged with a considerable degree of accuracy. It should be noted that the laboratory soil was not washed materials, as in the case of the river bed materials, and therefore gives a better criterion of evaporation from undrained normal soils. The results of these experiments are shown in Fig. 86, and Fig. 87 shows the results of a mechanical analysis of the materials used. From a comparison of these diagrams it will be noted that evaporation seems to decrease with depth more rapidly with the coarser materials or with the capillary power of the soil. In this connection it is worthy of note that the effects of capillarity have been found by various experiments to be approximately as follows:

TABLE 8.

Character of Soil	Capillary Limit Feet	Authority
Coarse Sand	4	Burr, Herring & Fuller
Find Sand	8	Burr, Herring & Fuller
Sandy Soil (moist)	5.5	Briggs and Lapham
Sandy Soil (moist)	4 to 6	Stewart
Fine Deep Desert Soil	25	Whitney

75. **Effects of Vegetation.**—The nature and extent of the vegetation on a surface have a marked effect on the amount of moisture delivered to the atmosphere from the soil. Experiments at the Wisconsin Agricultural Experimental Station show that barley, oats and corn require 13.2, 19.6 and 26.4 inches of rainfall, respectively, to produce a crop. (See Table 9). This includes the transpiration and evaporation from the cultivated surface as well as the actual quantity used by vegetation which is, of course, very small. The water simply serves to convey the soluble foods of the soil to the various fibres of the plant. The actual amount of water used in irrigation is not a fair criterion of the amount needed for the development of plant life as in most cases crops are over-irrigated. The actual depth of the rainfall and irrigation water used on crops varies from as low as twelve inches to several feet, frequently running into quantities much in excess of any ordinary rainfall in moist climates where irrigation is found to be unnecessary.

In the Report of the Kansas State Board of Agriculture for December 31, 1889, Mr. W. Tweeddale, C. E., gives Table 10 containing the results of investigations by M. E. Risler, a Swiss observer, upon the daily consumption of water by different kinds of crops.

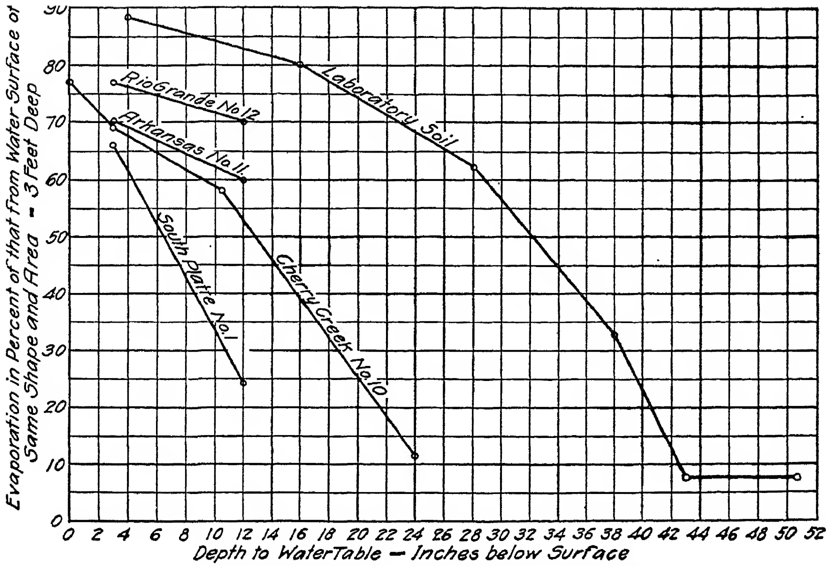

FIG. 86.—Evaporation from River Bed Materials.

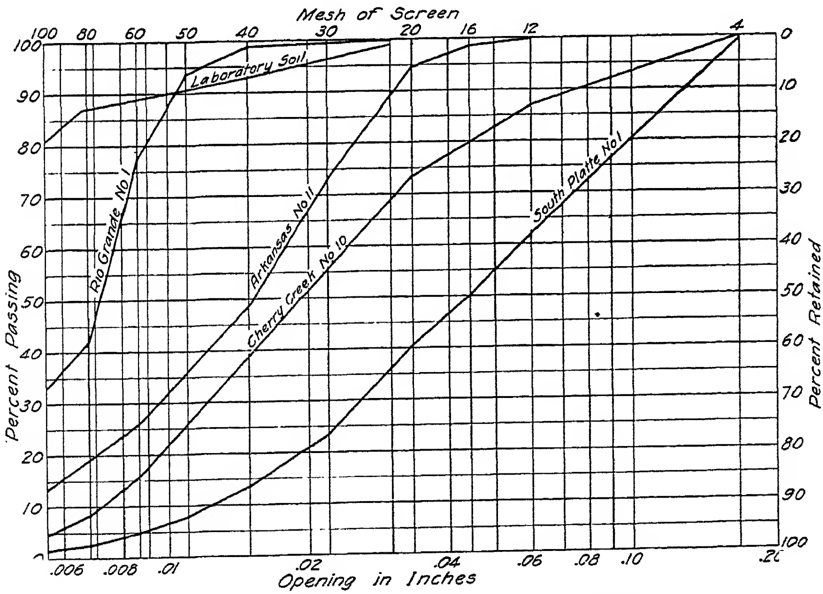

FIG. 87.—Mechanical Analysis of River Bed Materials.

TABLE 9.

The Amount of Water Required in Wisconsin to Produce a Pound of Dry Matter for Oats, Barley and Corn.

	Lbs. of water used	Lbs. of dry matter produced	Lbs. of water per lb. f dry matter		Computed yield per acre	Computed amount of water
				Mean.	Lbs.	In Inches
Barley	158.3	.3966	399.14	401.74		
Barley	141.03	.3488	404.33		7,441	13.19
Oats ..	224.25	.4405	509.31	501.47		
Oats ..	220.7	.4471	493.63		8,861	19.60
Corn ..	300.45	1.0152	295.95	301.49		
Corn ...	298.65	.9727	307.03		19,845	26.39

Mr. Tweeddale finds that this table agrees with careful experiments made in France and elsewhere, and calculates from it that from seed time to harvest cereals will take up fifteen inches of water and grass may absorb as much as thirty-seven inches.

TABLE 10.

Daily Consumption of Water by Crops

Crops.	Inches of Water. Minimum.	Maximum.
Lucern grass ..	0.134	0.267
Meadow grass	0.122	0.287
Oats	0.140	0.193
Indian Corn ..	0.110	1.570
Clover	0.140	
Vineyard	0.031	0.035
Wheat	0.106	0.110
Rye	0.091	
Potatoes	0.038	0.055
Oak trees	0.030	0.038
Fir Trees	0.020	0.043

The amount of moisture supplied to the air by forests is accomplished by several means:

a. Transpiration of soil water by the trees.
b. Direct evaporation of rainfall caught by the trees.
c. Evaporation from the soil of the forest bed.

Estimates for amount of transpiration can necessarily be only very

roughly approximated since it depends upon a large number of variable factors such as the amount of water at the disposal of the plant, the stage of its development, nature and amount of foliage, temperature, humidity, amount of sunlight, condition of soil and the weather conditions.[24]

Mr. W. Harrington [25] made an estimate of the quantity of water returned to the atmosphere by various kinds of vegetation based on the observations made by Wollny and others. At the locality in which the investigation was made the transpiration was concluded to be 6.5 inches during the same period the evaporation from free water surface was 8.39 inches. The transpiration was therefore 77% of the open water evaporation in this case.

From observations of rainfall under shelter of trees it has been concluded that the rainfall reaching the ground is on the average about 70% of that caught in the open. There was then 30% of the rainfall held by the trees which was directly re-evaporated, equivalent to 61% of open water evaporation for purposes of this estimate. The evaporation from the soil of the forest bed under the litter is according to various investigators from 13% to 67% of that from open water.

The total moisture added to the atmosphere through the influence of the forest compared with the evaporation from free water surface is given as:

Transpiration	77% of open water evaporation
Direct Re-evaporation	61% of open water evaporation
Forest Soil Evaporation	13% of open water evaporation
Total	151% of open water evaporation

For different kinds of vegetation, Table 11 based upon the investigation of Woolny, is of interest:

TABLE 11.

Kind of Vegetation	Water Returned to Atmosphere Proportion of Evaporation from Open Water
Sod	192%
Small Grain	173%
Forest	151%
Mixed Crops	144%
Bare Soil	60%

Zon[26] considers forests as the greatest evaporators of water, exceeding all other vegetable coverings and even exceeding the evapo-

[24] Report Chief of Forestry Division, 1889. B. E. Fernow.

[25] Forest Influences, U. S. Dept. Agr. Forestry Div., Bul. 7.

[26] Science, Vol. 38, p. 71.

ration from water surfaces. He quotes Otozky, a Russian soil physicist, as estimating the amount of transpiration from forests as nearly equal to the annual precipitation and is of the opinion that if the Atlantic Plain and the Appalachian regions were deforested it would have a perceptible influence on the humidity and consequently on the rainfall of the Central States and the prairie regions to the westward.

Tables 10 and 11, however, seem to indicate reasons for entirely different conclusions and to show that a decrease of stream flow may follow the destruction of forests and their replacement by meadows and cultivated fields on account of greater evaporation resulting therefrom. It is quite evident on the basis of these tables that if the drainage areas are covered by grasses or cereals, there might be comparatively little water left for the flow of streams. Observations in Wisconsin[27] indicate that little change occurs in the flow of streams after deforestation or after considerable drainage operations, but that about the same amount of water is vaporized by the second growth and the crops or other vegetation on deforested or drained areas. The character of the vegetation on a drainage area and its physical condition may however exert considerable influence on the amount of vapor that reaches the atmosphere.

The presence or absence of forests, as shown by observations in Germany, has also a marked effect on evaporation, directly from the ground or from ponds or lakes within the forested areas. From these observations Prof. M. W. Harrington[28] has compiled Fig. 88, page 149, which shows the effect on monthly evaporation. The upper curve represents the evaporation from water surfaces in the open country, while the lower curve shows the evaporation from water surfaces within forests. The shaded area thus shows the reduction in evaporation due to the protection of the forest.

76. General Principles.—Professor Cleveland Abbe[29] gives the following relations of evaporation, as established by Professor Thomas Tate:

(a) Other things being the same, the rate of evaporation is nearly proportional to the difference of the temperature indicated by the wet-bulb and dry-bulb thermometers.

[29] Preparatory Studies for Deductive Method in Storm and Weather Prediction, by Prof. Cleveland Abbe. Annual Rept. Chief Signal Officer for 1889, Part I, Appendix 15.

[27] The Flow of Streams and Factors that Modify it, by Daniel W. Mead, Bul. 425 of the University of Wisconsin.

[28] Bulletin No. 7, U. S. Dept. of Agriclulture, p. 97.

(b) Other things being the same, the augmentation of evaporation due to air in motion is nearly proportional to the velocity of the wind.

(c) Other things being the same, the evaporation is nearly inversely proportional to the pressure of the atmosphere.

(d) The rate of evaporation of moisture from damp, porous substances of the same material is proportional to the extent of the surface presented to the air, without regard to the relative thickness of the substances.

(e) The rate of evaporation from different substances mainly depends upon the roughness of, or inequalities on, their surfaces, the evaporation going on most rapidly from the roughest or most uneven surfaces; in fact, the best radiators are the best evaporizers of moisture.

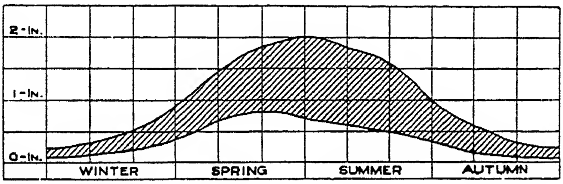

Fig. 88.—Reduction in Evaporation from Water Surface Due to the Presence of Forests (see page 148).

(f) The evaporation from equal surfaces composed of the same material is the same, or nearly the same, in a quiescent atmosphere, whatever may be the inclination of the surfaces; thus a horizontal plate with its damp face upward evaporates as much as one with its damp face downward.

(g) The rate of evaporation from a damp surface (namely a horizontal surface facing upward) is very much affected by the elevation at which the surface is placed above the ground.

(h) The rate of evaporation is affected by the radiation of surrounding bodies.

(i) The diffusion of vapor from a damp surface through a variable column of air varies (approximately) in the inverse ratio of the depth of the column, the temperature being constant.

(j) The amount of vapor diffused varies directly as the tension of the vapor at a given temperature, and inversely as the depth of the column of air through which the vapor has to pass.

(k) The time in which a given volume of dry air becomes saturated

with vapor, or saturated within a given percentage, is nearly independent of the temperature if the source of vapor is constant.

(l) The times in which different volumes of dry air become saturated with watery vapor, or saturated within a given per cent. are nearly proportional to the volumes.

(m) The vapor already formed diffuses itself in the atmosphere much more rapidly than it is formed from the surface of the water. (This assumes, of course, that there are no convection currents of air to affect the evaporation or the diffusion).

77. **Measurements of Atmospheric Moisture and Evaporation.**—The measurement of moisture in the atmosphere is accomplished by means of various forms of hygrometers and psychrometers, which, together with their use, are described in various meteorologies.[30] Some of these forms are in use at all of the regular stations of the U. S. Weather Bureau.

As the determination of evaporation by the Psychrometer is only roughly approximate and such evaporation also varies widely from year to year with other meterological conditions, it frequently becomes desirable for the engineer to determine from actual observations the evaporation which must be expected in connection with storage or other projects. Such experiments are usually made with round or square metallic pans of various depths placed either on or over the ground, or supported in the water and protected from waves in a suitable manner.

Milham says[31] "The amount of evaporation is usually determined by exposing large pans in the open and measuring the amount evaporated in a given time. These pans should have large area and considerable depth, so that the temperature will be approximately the same as the temperature of the surrounding areas."

Moore[32] illustrates an instrument designed by Prof. C. F. Marvin for use of the Weather Bureau. It consists of a large tank nearly filled with water, which is maintained at constant level by float on the surface of an auxiliary still basin communicating with the large tank by siphon. Whenever as much as .05 m.m. of water has evaporated, the fall of the float operates electrically to open a valve and admit just

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[30] See Meteorology, by W. I. Milham, pp. 197–203; Modern Meteorology, by Frank Walsh, pp. 141–145; Elementary Meteorology, by W. M. Davis, pp. 147–149; Meteorology, by Thos. Russell, pp. 34–38.

[31] Meteorology, by Milham, p. 193.

[32] Descriptive Meteorology, by Moore, p. 213.

enough water to restore the normal level. The quantity of water admitted is measured by an electrically recording tipping bucket, similar to those used in recording rainfall. Observations at Kingsburgh, California[33] by C. E. Grunsky, were made by use of pans, three feet square, fifteen inches deep and water maintained about 5″ below top of sides by replenishing when water had fallen about one-fourth inch, by using a calibrated measuring vessel. The pans were made of galvanized iron, a peg tapering to a point in the center of each pan extending up to the water surface. Two pans were used, one floated in the river, the other on land with sand banked around it to height of the water surface.

It has been found that the size, location and exposure of the pan have, as shown in foregoing sections, a considerable effect on the amount of evaporation, allowances for which must be made in order that such observations may be comparative. Biglow has found that there is a material difference in evaporation which will obtain from various sized pans, due partially at least to the more rapid removal of the vapor bank from the smaller vessels by the wind, and that the relations between evaporations from a lake surface and from pans of various sizes and locations are essentially as shown on Table 12. It seems doubtful that this table can be taken as the last word in regard to this evaporation re-

TABLE 12.

Evaporation Relations between Lake Surfaces and Pans of Various Sizes and Locations[34]

Size and Location of Pans	Percentage of Evaporation
Lake Surface	100 per cent.
Land Pans 2 feet square	175 per cent.
3 feet square	162 per cent.
4 feet square	150 per cent.
6 feet square	130 per cent.
Floating Pans 2 feet square	140 per cent.
3 feet square	130 per cent.
4 feet square	120 per cent.
6 feet square	104 per cent.

lation, but it simply indicates the present status of the knowledge of this subject.

[33] Eng. News. Aug. 13, 1908.

[34] See American Civil Engineers' Pocket Book (second edition, 1912), p. 1250; also Trans. Am. Soc. C. E., Vol. 80, 1916, pp. 1843–1858.

It would seem that not only the size of the pan, but that its material, depth and color would have a considerable effect upon the evaporation results, and in each instance evaporation percentage should be established only after a careful consideration of the conditions in detail. Observations should also be made of atmospheric and water temperatures, wind movements and absolute humidity. Unfortunately, the observations which are made and published are often deficient in the essential data which would make them of general value for comparative purposes, and when used without such data they are often misleading.

78. **Importance of a Knowledge of Evaporation and Atmospheric Moisture in Engineering Studies.**—The entire question of atmospheric moisture has an important bearing on the problems of distribution and local intensity of precipitation, and a knowledge of this subject is requisite for a proper understanding of rainfall which is of great importance to the engineer. It should be noted that water vapor under similar conditions of temperature and pressure is lighter than air and that moisture laden air is lighter than dry air (see Section 61); hence there is a decided tendency for the moist air near the land or water surface to rise through the drier and heavier upper air strata. It should also be noted that as the amount of moisture in each unit of air at the equator is six times the amount in each unit at the poles, the air at the equator is lighter than the air at the poles on account of its contained moisture as well as its higher temperature, and thus serves to increase pressure differences and consequent general atmospheric circulation.

Evaporation and transpiration also have important effects on stream flow as will be discussed in a later chapter, and their influence must be understood for a correct appreciation of many problems of water supply. A knowledge of evaporation is of direct importance to the engineer in the investigation of storage projects, water supplies for canals, etc., as the net amount of water which can be retained by reservoirs, or will be needed for canals, is profoundly influenced by the evaporation which will take place during the year or the period of use. As previously noted (see Section 65) the monthly evaporation from free water surfaces in many parts of the United States is equal to or greater than the monthly rainfall in the same area; hence the water available in any reservoir will be the difference between the runoff from the drainage area which feeds the reservoir, plus the rainfall on the reservoir surface, less the evaporation from such surfaces, plus other losses such as percolation, etc., and less any amounts abstracted

for use. A minimum exposure of surface to evaporating effects is therefore usually essential to economic storage; that is to say to eliminate evaporation so far as practicable at the reservoirs there should be the greatest practicable depth. A study of the effect of areas on the water supply which might be secured each month from an Eastern stream in a reservoir having an area equal to the vari-

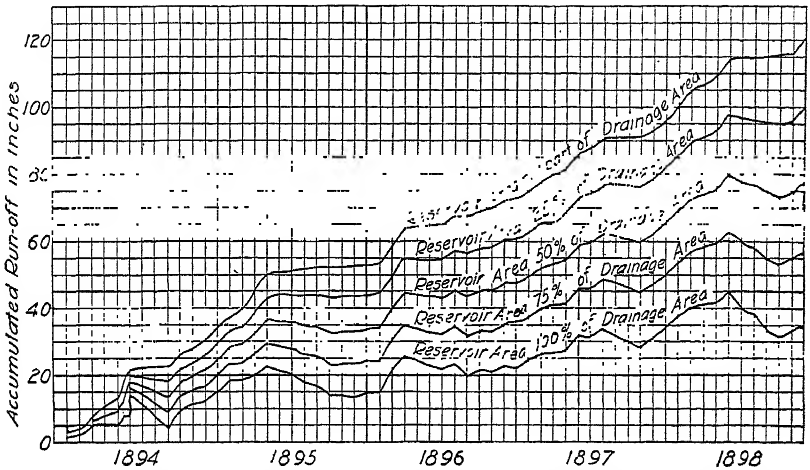

Fig. 89.—Cumulative Storage as Modified by Evaporation from Reservoirs of Various Relative Areas.

ous percentages of the drainage areas, from which the water is received, is shown in Fig. 89.

79. **General Conclusions.**—The study of evaporation has not as yet been carried far enough to warrant any definite general conclusion which can be reduced to a formula by means of which the monthly or annual evaporation at any locality and under definite conditions of exposure can be calculated from the Weather Bureau data for temperature, humidity and wind movements. Nevertheless sufficient information is available that by a study of the conditions and the results of the various experiments together with the Weather Bureau records, rough approximations can be made which will give an idea of the extreme variations which are liable to occur. As in all other engineering calculations, an allowance for ignorance of this subject must be made by factors of safety, the magnitude of which may perhaps be decreased with further study and investigation.

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See also references on Evaporation from Soils given in Table 7, page 142.

CHAPTER VII

PRECIPITATION

80. Precipitation—The Ultimate Source of all Water Supplies.—All available water supplies, including the surface waters of lakes and swamps, the water flowing on the surface and in brooks, creeks and rivers, the waters of springs, the waters standing in or flowing through the subterranean strata, including all waters available for agriculture, for public and private water supplies, for irrigation, for water power, for navigation and for other purposes, are derived primarily from precipitation. Deficient precipitation, or rainfall much below the average, may result in insufficient supplies for any or all of these purposes unless the shortage has been duly foreseen and provided for by suitable engineering construction. On the other hand, a super-abundance of rainfall may produce undesirable conditions. When heavy rains occur in a short period of time, they frequently produce disastrous floods and overflow conditions which may be seriously detrimental to human interests. Even normal rainfall may be locally injurious when lands are level and drainage conditions are imperfect, or when lands receive excess drainage from higher surrounding lands or overflow from streams which may inundate or saturate them temporarily or permanently and render them more or less unsuitable for agriculture or other utilitarian purposes. Under these conditions the successful reclamation of such lands may make systems of drainage ditches or of levees and other engineering works essential for protection.

In all of the problems of the hydraulic engineer, arising from a deficiency or a superabundance of water, or from the necessity or desirability of utilizing the water resources of a country in various ways and for various purposes, the questions of the quantity of rainfall and of its occurrence, distribution and influence are fundamental to such problems and of great importance in their solution. Many of the problems with which the hydraulic engineer has to deal are directly affected by precipitation; and in many other cases, the influence is indirect but important. The subject of precipitation, therefore, deserves careful study and investigation.

81. The Practical Consideration of Rainfall.—The engineer is particularly interested in rainfall as it affects surface water or runoff and

ground water or underflow, and especially in the maximum and minimum intensities and quantities of flows which have occurred in the past, and which must therefore be anticipated in the future from given drainage areas or from given ground water sources. The rainfall and its distribution affect questions of climate, sanitary conditions, agriculture, irrigation, drainage, public and private water supplies, water power, flood protection, river regulation, internal navigation, and many other problems with which the engineer has to deal. While rainfall is only one of numerous factors in most of these problems, it is an important one for without rainfall there would be no runoff or underflow, and there could be no animal or vegetable life.

If accurate long time and detailed records of local rainfall are available, conclusions as to the rainfall conditions that may occur in the future are best answered by the consideration of those known to have occurred in the past, that is by the actual rainfall records of the locality. Records sufficient in extent for entirely satisfactory use are seldom available, as few records are of great length, and those few are often considerably in error.

When extended local records are not available, the answer to the questions of the probable future rainfall conditions becomes more difficult and can be answered only by a careful and extended study of the rainfall conditions in other localities, with due allowance for the great differences which are liable to exist in local conditions.

In the study of rainfall data, details are essential and generalizations are of little value. For hydrological study, variations in yearly rainfall and the varying distribution throughout the various years are of greatest importance. Averages are only of general interest. The questions of the frequency in occurrence of periods of extreme rainfall, either maximum or minimum, and the rate and distribution of rainfall for such periods, are matters of importance in both engineering and agriculture. If rain commonly occurs in adequate amounts at times when most needed and under conditions where it can be best utilized, it becomes an asset of great value; whereas if it occurs at seasons when it cannot be utilized or under unfavorable conditions of intensity and distribution, it may become of serious import.

The influence of rainfall on the flow of streams and on ground water is so direct that those unfamiliar with the subject are apt to assume that the relation may be represented by some simple expression and that, therefore, if the rainfall for a period of years be known, the cor-

responding stream flow and the amount of water available in the underflow, may be directly and readily calculated therefrom. Upon acquiring only a brief familiarity with the subject it becomes evident that no such simple relation exists and that the relationship is in fact complicated by a multiplicity of other physical conditions which have an important if not an equal influence.

Observations of stream flow are quite limited both in time and geographical extent, while the observations of rainfall have extended over a considerably greater period of time and the points of observation of rainfall are also geographically much more widely distributed. If, therefore, it is possible to trace any relationship between the flow of streams or of the underflow of ground water and the rainfall and other physical conditions on the drainage areas that will enable the engineer to calculate or estimate the stream flow even approximately, such relationships become of great value to the hydraulic engineer on account of the lack of other more definite information. It is therefore important that the engineer inform himself as fully as possible on the relations that exist between rainfall and stream flow and the modifications of those relations by other physical factors. By such means the information regarding recorded rainfall, sometimes available for long terms of years, may be applied to the problem of stream flow and ground water supply, in which the engineer is often directly concerned.

The engineer is frequently obliged to draw conclusions of greater or less importance, often from very inadequate data, as to rainfall and the resulting ground water supply or surface runoff, and their possible extremes from some given source or drainage area. In such cases, the engineer may be obliged to estimate the probable and possible rainfall conditions from comparisons with other areas where such data, also frequently inadequate, are available and which areas are similarly located geographically, topographically and meteorologically, and where, on account of such similarity of location and conditions, similar intensity and magnitude of rainfall may reasonably be anticipated.

It is readily demonstrable that local conditions are never exactly duplicated, and that any comparisons between apparently similar localities are subject to possible errors of considerable magnitude. Hence, estimates of rainfall and runoff, and the design of structures based on these comparisons, must for safety be made with these probable errors in mind, and must include factors of safety proportional to the possible casualities which might result from designs based on such erroneous data.

In considering these problems it is important to recognize that general principles are frequently subject to wide variations, and even to marked exceptions, especially when relating to the complicated subject of meteorology. It is highly essential therefore in assuming that any general principles may or will obtain in a given locality, to secure sufficient data to demonstrate that all conditions are favorable to the probable prevalence of such principles and the probable force or intensity of the phenomena resulting thereunder. It must also be remembered that only limited conclusions should be drawn from limited observations. In many cases, conclusions based on data for single months or years would be entirely reversed if based on observations for other periods of equal length, and both would be altered if based upon the average or extremes shown by long series of observations.

In these various questions of engineering importance, even the best information is generally incomplete and unsatisfactory. The rule to be followed is to make all investigations as complete as permissible and to limit assumptions so far as possible. On account of its great importance to the engineer, the subject of rainfall is therefore discussed in as much detail as space will permit.

82. Causes Which Produce or Influence Precipitation.—A discussion in anything like adequate detail, of the causes which produce precipitation and which influence its distribution, its total amount, and its variation, would be too extended for our purpose. From their very nature, great uncertainty is involved in these questions, for the factors are not only world wide but probably involve influences which relate to the whole solar system, or at least to direct solar influences on the atmospheric conditions of the earth. It is probable that this subject will never be understood in detail, but long observations and study will undoubtedly greatly extend human knowledge of the principal factors and their most important influences.

In general, the source of precipitation is the water taken up by evaporation from wet surfaces. The immediate vicinity of large bodies of water from which the most extensive evaporation necessarily takes place, and of extended areas of vegetation from which great quantities of water are transpired during periods of development and growth, are, therefore, the most important requisites for extensive precipitation. In general, distance from extensive sources of supply results in a decrease in annual precipitation. These conditions are, however, greatly modified by the direction of the wind, which, as has been pointed out, is largely dependent at least for a considerable portion of

the earth's surface, on atmospheric pressure and the passage of the great centers of cyclonic atmospheric movements around the globe. The present opinion of meteorologists on the subject of causes of rainfall is set forth by Blanford as follows:

"As a result of a long study of the rainfall of India, and perhaps no country affords greater advantages for the purpose, I have become convinced that dynamic cooling, if not the sole cause of rain, is at all events the only cause of importance, and that all of the other causes so frequently appealed to in popular literature on the subject, such as the intermingling of warm and cold air, contact with cold mountain slopes etc., are either inoperative or relatively insignificant." [1]

The ascensional movement of moist air which results in dynamic cooling, and consequently in precipitation is brought about in one of three different ways:

(1) By convective currents.
(2) By hills and mountains.
(3) By cyclonic circulation.

Curtis [2] classifies rainfall as convective, orographic or cyclonic, according as it is due to the first, second or third of these causes of ascensional movement. In some cases two or all of these causes may be operative at the same time.

1. Under conditions of purely *convective* rainfall, the heat and moisture of the atmosphere cause the circulation to be primarily vertical, and the local evaporation is largely precipitated without being carried away by horizontal currents. In such cases increased evaporation will result in an increased rainfall and any change in surface condition which increases or diminishes the evaporation will, under such a condition, be followed by a corresponding increase or decrease in precipitation.

Curtis says: "The equatorial rain belt is the most prominent region with almost exclusively convective rainfall. The Brazilian forest region, the Aruwhimi district of central Africa, the Malaysian Archipelago, and the valley of Upper Assam in India are in or near this belt. They have light winds, and the moisture evaporated from the surface is precipitated before being carried to any considerable distance by horizontal currents. Under these conditions an increase or de-

[1] Nature, Vol. XXXIX, p. 583.

[2] Analysis of the Causes of Rainfall, G. E. Curtis. Forest Influence. Bul. No. 7, Forestry Division U. S. Dept. Agriculture, p. 187.

crease in the evaporation will be followed by an increase or decrease in rainfall. * * *

"Blanford estimated that for the Aruwhimi district probably over half of the rainfall is due to the direct restoration of the moisture evaporated. * * *

"Bordering on each side of the equatorial belt are the regions of the trades, which, over the ocean, are almost rainless; but over intercepting land areas, such as Central America and the Antilles, considerable rainfall occurs. This is frequently difficult to analyze, but it is largely convective and in hilly regions partly orographic. The seasonal distribution shows that the rainfall is intimately related to the annual oscillation of the limits of the trade-wind, and that the rainy season requires a special explanation. With the exception of the well known tropical cyclones of the seas, the distribution of pressure over the trade region is unfavorable to the development of a cyclonic circulation, and consequently, cyclonic rainfall is seldom presented."

2. Under conditions of *orographic* rainfall, horizontal moist air currents are forced to rise by the hills or mountains that they encounter in their path. In such cases the moisture evaporated in the region lying to windward may be partially or entirely precipitated over the slope and the region to windward where the ascensional movement is developed. An increase in evaporation under such conditions may be restored to the basin by increased precipitation. The extent to which this restoration of moisture lost by evaporation will take place will depend on the topographical conditions and the frequency and direction of the winds.

The heavy rainfalls on the Northern Pacific Coast of the United States and on the Southern Appalachians in North and South Carolina are examples of orographic rainfall. The rainfall on the Pacific Coast is due to the passages of cyclonic storms from the Pacific, and the rainfall of the Carolina highlands is largely due to the interception of the West India hurricane by the Southern Appalachian Mountains.

3. The conditions of *cyclonic* rainfall include the great variety of rain types related to cyclonic circulation. This is the type of rainfall which is most common in the United States east of the Rocky Mountains.

Moore [3] has pointed out the main controlling factors influencing rainfall in the Eastern United States as follows:

"Before one can get a comprehensive idea of the magnitude of the

[3] Report on the Influence of Forests on Climate and on Floods, p. 20—Government Printing Office, Washington, 1910.

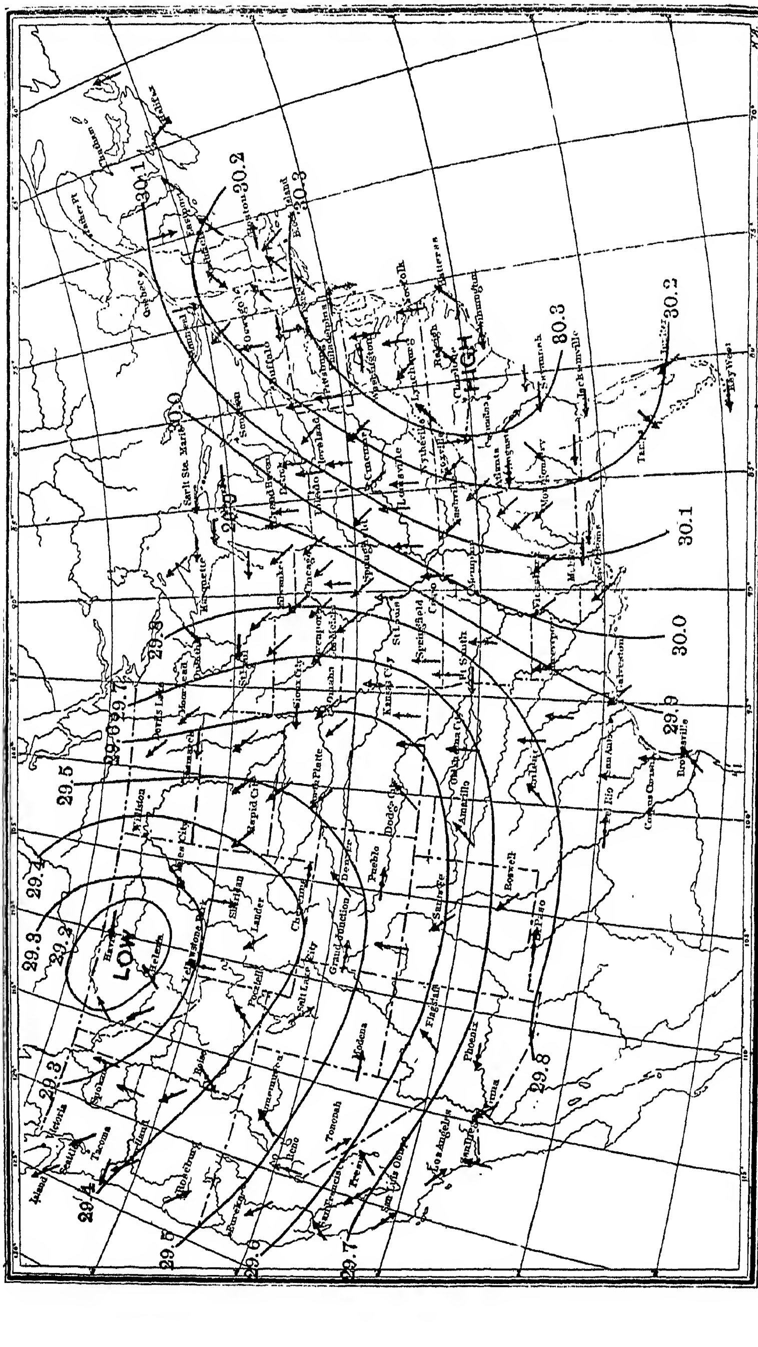

Fig. 90.—Source of Rainfall in Eastern United States. Arrows fly with the wind and show how the moist atmosphere of the Gulf of Mexico and Atlantic Ocean is drawn inland (see page 163).

problem involved in the creation of floods of the United States, it will be necessary for him to first study Fig. 90, page 162 which gives a typical illustration of the cyclonic storms that frequently form on the Rocky Mountain Plateau, either on its northern, central, or southern portions. Under the influence of gravity air flows from regions where the pressure is great toward the regions where it is less. In the case illustrated by Fig. 90 the atmosphere, as indicated by the direction in which the arrows point, is flowing from the region marked "high," which is central over the Carolinas, toward the region where the pressure is low, which is central over Montana, and the vaporous atmosphere that rises from the Gulf of Mexico and the adjacent ocean (and the marginal and interior lands—*Author*) is carried far into the interior of the continent. Conditions similar to these occur many times each month, and as a result, the eastern and central portions of the United States are bathed in a succession of rains which, as shown by Figs. 109, 110 and 111, pages 201 and 204, gradually thin out and largely disappear on the eastward edge of the Rocky Mountain Plateau, because the currents of air from the Gulf of Mexico do not reach farther inland."

Curtis says: "In the ordinary progressive area of low pressure the cyclonic circulation is largely horizontal, but with an upward component. This upward component produces the usual rainfall of our cyclonic storms. In these storms the horizontal component of the circulation is so large that the moisture evaporated over one region is precipitated over another. Consequently, in regions where rainfall is of this type, an increased evaporation in any region will not be followed by an increased rainfall in that same locality.

"In the local thunder storms we have a type of rain related to a cyclonic circulation in which the vertical component often becomes very large, as compared with the horizontal component. This predominating vertical component is due to convection and the accompanying rainfall is to be considered as partly or largely convective. Convection induces and initiates a cyclonic circulation which may continue after the direct convective action has ceased. * * * "

83. **Sources of Atmospheric Moisture.**—The atmospheric vapor from which the rainfall is derived is replenished by evaporation from the free water surfaces of creeks, rivers, lakes, swamps and oceans, from the moist soil and other surfaces wet by precipitation, and from the transpiration of plants which draw their moisture from the soil waters, sometimes from many feet below the surface.

The oceans which cover three-fourths of the surface of the earth are the chief source from which atmospheric moisture is derived and from which the precipitation of the earth as a whole is most largely furnished. The ocean is also the principal source of rainfall of the islands and of the lands adjoining the continental coasts especially those near the paths of cyclonic storms from the seas toward the lands. The precipitation on continental interior lands is, however, the phenomenon in which the engineers are more generally interested, and the source of this precipitation is derived most largely from the moisture that obtains from the continental evaporation, from land surface and from the surfaces of rivers, lakes and swamp areas, and indirectly by the transpiration from animal and vegetable life. By far the greatest portion of the rain falling on continental areas is thus returned to the atmosphere, for the discharge of the rivers of a continent into the seas will not equal half of the continental rainfall. (See Table 13, page 165).

While a certain portion of the amount of precipitation retained from the runoff sinks into the strata and, in some cases, may flow underground to the sea, thus neither appearing in runoff nor adding to atmospheric moisture, and a small amount of the rainfall is taken up and forms part of permanent vegetable and animal growth, yet these losses are comparatively insignificant, and by far the greater portion of the rainfall not appearing as runoff is as a rule directly or indirectly evaporated into atmospheric moisture.

From one-half to perhaps two-thirds of the average rainfall is therefore probably evaporated into atmospheric moisture and unites with the ocean vapor in the great atmospheric storehouse of moisture from which rainfall is derived.

The average rainfall of the United States is estimated at about thirty-six inches. From eighteen to twenty-four inches of this is probably re-evaporated and the difference, aggregating from twelve to eighteen inches, is supplied from the oceans and gulf waters which adjoin the country.

When the moisture from the oceans is precipitated on the land closely adjoining the coast, on account of parallel mountain ranges (as in the case of the Sierra Nevada Mountains of the U. S.) and in consequence when the lands beyond the mountain ranges receive little moisture from the ocean, the evaporation from such lands is gradually moved eastward by the easterly atmospheric drift and the country must be a desert. Even when no mountains exist close to the ocean, the ocean moisture is usually precipitated not far from the coast line and the precipitation on

the interior is most largely derived from interior sources of evaporation. There is no doubt but that the precipitation along the coast is ultimately evaporated and moves inland with the succeeding storm movements while much evaporation from the land is carried to the sea in the same way.

84. **Geographical and Topographical Conditions Affecting Precipitation.**—While various causes may be active in the production of rainfall, by far the greater portion of precipitation is caused by the expansive cooling of air as it ascends, due to cyclonic, orographic, or convective circulation, as produced by the passage of storm centers, the existence of mountain chains or the vertical currents of moist air during calms or within enclosed intermountain areas.

TABLE 13.

Approximate Average Rainfall, Runoff and Evaporation from Various Drainage Areas

Drainage Area		Mean Rainfall	Mean Runoff	Mean Evaporation	$\frac{\text{Evaporation}}{\text{Rainfall}}$ = % Evap.
Great Lakes	1882–98	31.4	11.6	19.8	63
Genesee River	1890–98	40.3	14.2	16.1	65
Croton River, N. Y..	1877–98	49.4	22.8	26.6	54
Sudbury, Mass.	1875–1900	46.1	22.6	23.5	51
Neshaminy, Pa.	1881–99	47.6	23.1	24.5	53
Hudson River	1888–1901	44.2	23.3	20.9	47.5
Connecticut	1872–85	43.0	22.0	21.0	49
Upper Mississippi ..	1892–95	24.6	3.6	20.99	85
DesPlaines, Ill.	1896	39.6	6.7	32.9	83
Platte, Neb.	1894	12.8	1.0	11.8	92
Wisconsin River ...	1903–08	33.7	21.8	11.9	35
Chippewa River	1904–08	32.5	16.2	16.3	50
St. Croix, Wis.	1902–04	51.4	17.1	34.3	67
Rock River, Wis. ..	1904–08	32.2	6.8	25.4	79

Precipitation may therefor be greatly modified by the location of the area considered relative—

a. To large bodies of water or other sources of vapor.

b. To the tracks of cyclonic storms.

c. To altitude, and especially to the presence of mountain ranges.

It is especially important to recognize that these influences are interdependent, and that the effect of one element may so dominate or obscure the effect of others as to render them, even in extreme cases, largely insignificant.

85. Precipitation in Relation to Location near Bodies of Water and Tracks of Cyclonic Storms.—Figs. 66, 67 and 68, pages 120 and 121 show clearly the effect of the oceans and lakes on the absolute and relative humidity of the adjacent lands of the United States. The effects of distances from these sources of supply on local precipitation are also shown in general both by these same maps and by Fig. 109, page 201, which shows the mean annual rainfall of the United States.

The removal of aqueous vapor by mountain heights, and the resulting decrease in precipitation in areas beyond such elevations, are also illustrated by the area of the country just east of the western mountains. This area, although near an abundant source of supply, is practically deprived of its value by the intervening mountain ranges.

The small rainfall in southern California, in spite of its location close to the Pacific Ocean, illustrates the necessity of favorable wind currents in order that adequate precipitation shall result. The precipitation in the area east of the Rocky Mountains rapidly decreases in quantity as the distance increases from the Gulf of Mexico and southern Atlantic, although the vapor is carried from these sources and from the moist land along their borders far into the northwest portion of the country by reason of the influence of the frequent slow passage of low areas of atmospheric pressure or cyclonic storm centers which cause the moist atmosphere to flow farther inland, but overcome distance only to a limited extent. In the case of Montana and the Dakotas, located within the track of the most numerous storms of the continent the limited effect is not sufficient to produce rainfall equal to the average in the United States. In the southwest, the comparative freedom from the passage of these storm centers limits the atmospheric movements in a westerly direction and gives rise to semi-arid conditions, comparatively near to abundant sources of moisture.

86. Occurrence and Distribution of Rain Storms.—The origin of cyclonic storms, which are one of the principal causes of precipitation, and the varying paths of the same across the United States, have been discussed in sec. 38 *et seq.* As the air expands and rises at and near the center of low pressure, a reduction in temperature occurs through direct contact and mixing with colder bodies of air, through direct radiation of heat to the surrounding space and especially through expansion without material transmission of heat. As soon as the dew point is reached, clouds are produced which consist either of condensed moisture or of even moisture congealed into minute crystals of ice. The clouds are ordinarily carried high in the atmosphere to the

northeast of the center of low pressure by the winds from the south which reach and join the cyclonic whirl. As the intensity of the circulation increases and moist air is drawn from humid sources with favorable conditions, these clouds thicken and become so dense by the resulting condensation of vapor that precipitation begins to increase in quantity at or near the center of low barometric pressure. These areas of precipitation are popularly stated to be in the southwest quarter of the minimum pressure area where perhaps the most intense precipitation may normally occur, but an examination of the weather maps shows that in few cases is precipitation confined to that locality. With the passage of the low or storm center, the rotating cyclonic winds change in direction and the cold and usually dry winds from the northwest and north, begin to flow, taking up the moisture, and the clouds disappear with resulting clear and cooler atmospheric conditions.

The above may be regarded as the general rule of purely cyclonic rainfall. The actual occurrence of rainstorms, however, is generally complicated by topographical and barometric conditions, and the general distribution of the rain is frequently far more extended than the above description would indicate. Examinations of the weather map seem to indicate that the rainstorm frequently follows in the general path of the cyclonic center long after its passage and even extends to and under the anti-cyclonic or high pressure center. The general law seems to prevail to a greater extent as the centers of low and high pressure increase in intensity.

87. **Effects of Altitude on Precipitation.**—Mountains, and especially mountainous ranges, as elsewhere noted, have a marked effect on atmospheric movements, and hence on precipitation.

a. Mountains intercept the low lying, rain-bearing clouds.

b. When located in the path of atmospheric movements, the lower prevailing winds are forced upward, giving rise to rapid cooling and hence to precipitation when the winds are burdened with moisture.

c. Mountains also cause local atmospheric circulation and consequent orographic rainfall.

From the presence of clouds at 3,000 to 7,000 feet above sea level it is reasonably assumed that the dew point is most commonly attained in the atmosphere at these elevations, and for the same reason, that the greatest relative amount of rainfall ordinarily occurs at these altitudes. The rainfall on lower elevations is supposed to be decreased somewhat by the evaporation of the raindrops falling through non-saturated air. In the

arid portions of the country, apparently quite a heavy precipitation from a cloud may often be seen, when only a trace or perhaps no rain reaches the ground, all or nearly all of the water being evaporated during its fall. The author has been unable to find any data to substantiate the claim of a decrease in rainfall above the normal cloud elevations.

The presence of mountains across the path of cyclonic atmospheric movements causes an upward flow, a consequent cooling and a precipitation of the contained moisture which frequently affects the quantity of rainfall at higher altitudes and also at considerable distances to windward of the actual elevation.

The altitude at which the maximum rainfall occurs is higher in summer than in winter and occurs at an elevation of from 3,000 to 7,000 feet. In the Alps, the maximum rainfall is found to occur at an altitude of about 4,000 feet in the winter, while during the summer the maximum rainfall occurs at an elevation greater than is covered by the records.

The effect of the prevailing direction of moisture-laden winds modifies the general rule to a considerable extent since mountains thus have greater rainfall on the windward side than on the leeward side. This condition is perhaps best illustrated by the mountains of the northwest coast in which the rainfall increases rapidly with the elevation, but is much greater on the westward than on the eastward side.

The plateaus of Southern Utah, which rise to an elevation of more than 10,000 feet, are apparently well watered as they support an extensive forest, while the surrounding lower country is practically a desert. This condition is shown on nearly all mountains of the United States, more strikingly perhaps upon the western mountains which for the most part are surrounded by semi-arid plains upon which trees may grow only along the water courses, while the mountains themselves are thickly clothed with forest growth above a certain altitude and nearly up to the region of perpetual snow.

In the United States, the absence of records at the high elevations makes it impossible to determine with certainty the relation which exists between rainfall and altitude in any given region. It is known that the relation is not the same at different places, according as these localities are subject to the various influences of winds, neighboring topographical features, and other conditions which affect the processes of precipitation.

That rainfall increases with altitude is a local and not a universal principle. That the rule is broadly true makes the general assump-

tion common and often misleading. In considering the amount of rainfall with respect to water supply, it is not safe to count on this principle in localities where it is not known to prevail, for in some cases no such increase is found, and in other cases even a decrease in rainfall with altitude occurs.

The attempt to establish formulas for such increase, unless such formulas are understood to be for very local and restricted use, is misleading and dangerous. The problem therefore must always be one of local study and investigation.

88. **Minor Influences.**—The extent of the influence exerted upon the amount and distribution of precipitation by minor physical conditions is at best uncertain. The opinion that the presence of forests largely affected such distribution was formerly quite general and considerable data have been offered to sustain this hypothesis. The effects, if any, are within the limits of the errors of observation, and hence of little value as proof either for or against the assumption. Standing within the shade of a dense forest of mighty trees the assumption of their importance as a factor in the production of precipitation may seem warranted, but if the same forest be viewed from a neighboring mountain top, its apparent insignificance in controlling or even influencing such vast atmospheric forces seems conclusive. Meteorologists have in general concluded that the presence or absence of forests has little or no influence in modifying rainfall.[4] The occurrence of rain over the dense forests of the Pacific Coast and in the tropics has been even lately advanced as an argument in proof of the effect of forests on rainfall under at least special conditions. It is evident, however, that the forests exist because of suitable rainfall conditions, and it is fair to assume, unless further evidence is produced, that the forests are due to the prevailing rainfall conditions rather than that the rainfall is due to the existing forests. It would seem that in this case, cause and effect are somewhat confused in the minds of some observes. (See Fig. 91, page 170.)

89. **Rainfall Maps.**—The Daily Weather Map of the United States, published by the Weather Bureau at Washington, D. C., and also issued by a number of the important stations of the Weather Bureau shows the barometric pressure, temperature, direction of the wind at

[4] See Meteorology, Thomas Russell, p. 86. Forests and Rainfall, H. A. Hazen, Monthly Weather Review, 1897, p. 395. The Relation of Forests to Rainfall, W. F. Hubbard, Monthly Weather Review, Jan. 1906, p. 24.

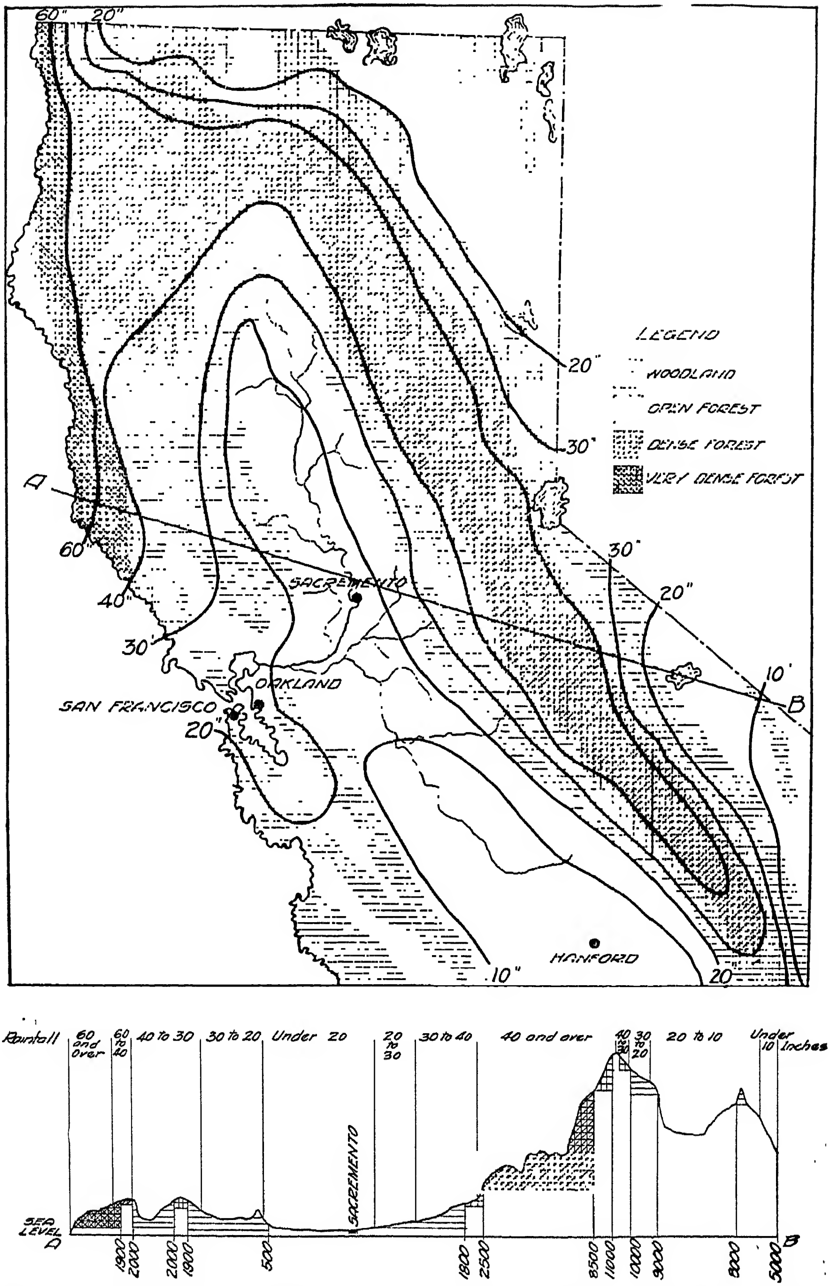

FIG. 91.—Distribution of Annual Rainfall and Forests in California (W. F. Hubbard, Monthly Weather Review, Jan., 1906). (See page 169).

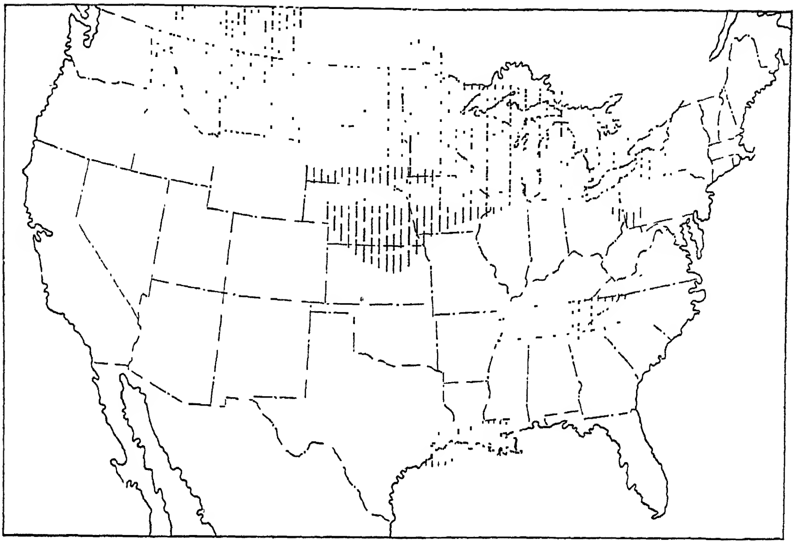

Fig. 92.—Rainfall Conditions in the United States at 8 A. M., July 16, 1907 (see page 172).

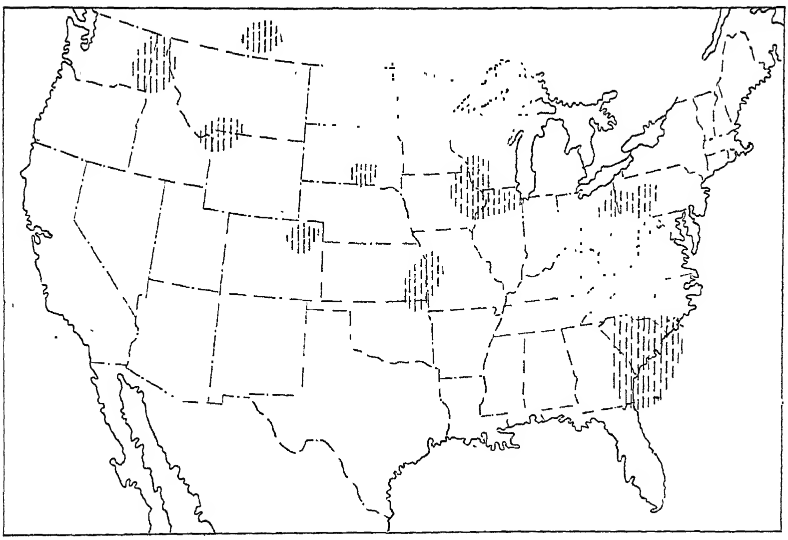

Fig. 93.—Rainfall Conditions in the United States at 8 A. M., July 17, 1907 (see page 172).

8:00 A. M., Washington Time, and the precipitation that has occurred in the last 24 hours. In the National Weather and Crop Bulletin, which is published by the Weather Bureau weekly from April 1 to October 1, and monthly for the remainder of the year, maps of the weekly and monthly rainfall are also given. Maps of the monthly rainfall are also given in the publications of the Monthly Climatological Data and in the Monthly Weather Review, and rainfall maps of annual precipitation, temperature, etc., are published in the Annual Summary of Climatological Data, the annual number of the Weather Review and the Annual Report of the Chief of the Weather Bureau. Occasionally maps are also given in the Weather Review showing the data for storms of exceptional magnitude. These publications also give the data from which the path of each storm and the resulting precipitation can be platted.

For many engineering purposes the annual or even the monthly maps of rainfall are only of general value; a more detailed study of the actual occurrence of rainfall is essential and the data should be secured and platted in order to bring out the facts necessary to develop the information needed.

90. **Occurrence of Precipitation.**—The geographical distribution of rainstorms seems largely fortuitous. Individual rainstorms never occur twice over exactly the same geographical extent of territory nor with equal intensity at any points within the territory covered. They are not only irregular in their distribution but progressive in both their distribution and intensity, changing from hour to hour during their occurrence. The extent of a somewhat general rainstorm in progress at 8:00 A. M. (Washington time) over the Northwest on July 16, 1907, is shown by Fig. 92, page 171. On the area over which this storm extended, the actual precipitation varied widely and the extent of the storm rapidly changed from hour to hour. At 8:00 A. M. on July 17 the general rainfall had ceased and the storm had become localized as shown by Fig. 93, page 171. The varying character and extent of the rainfall as illustrated by those two maps show the extremes of one storm which affected the Northwest, and illustrate, in a general way, the irregularity and lack of uniformity in rainfall occurrence and distribution. (See also Fig. 31, page 70).

It should also be noted that the periodic rainfall maps issued by the Weather Bureau for weekly, monthly or annual periods are the results of the summation of irregular distribution of numerous rainstorms, the irregularities of which can perhaps be more clearly shown

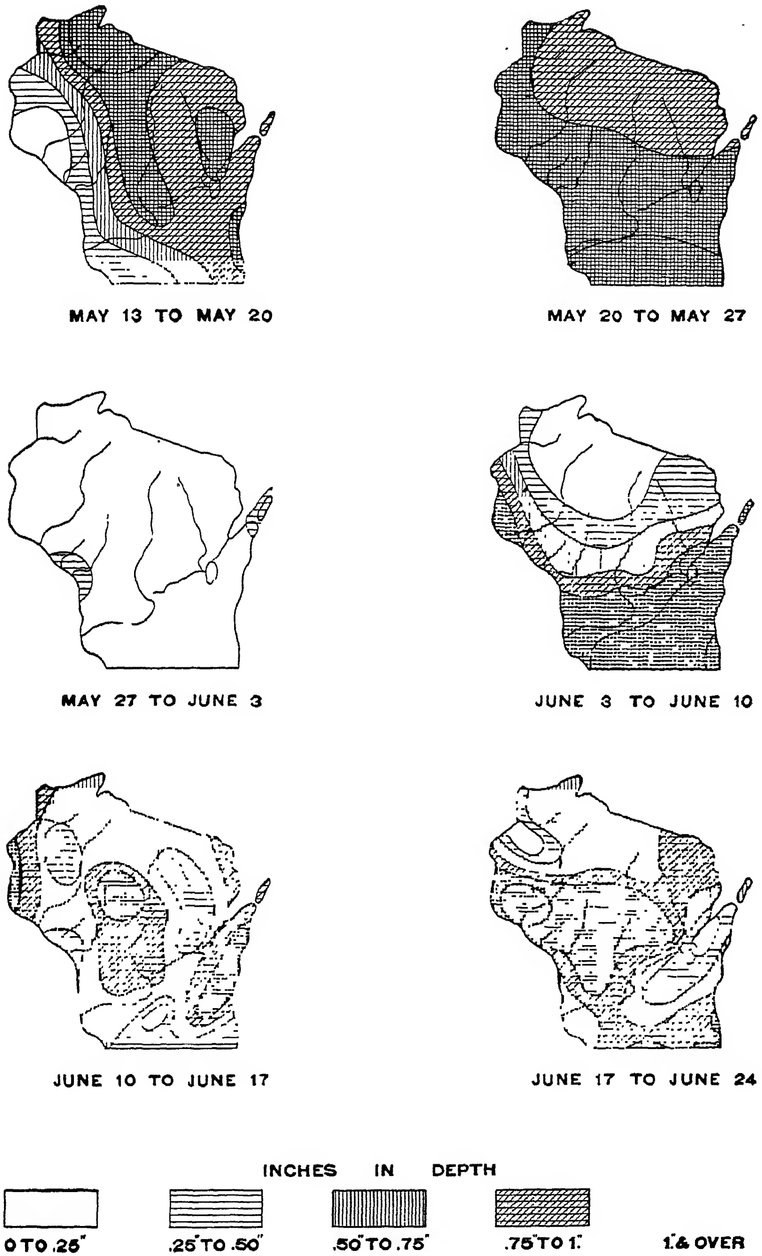

Fig. 94.—Distribution of Weekly Rainfall in Wisconsin, 1907 (see page 175).

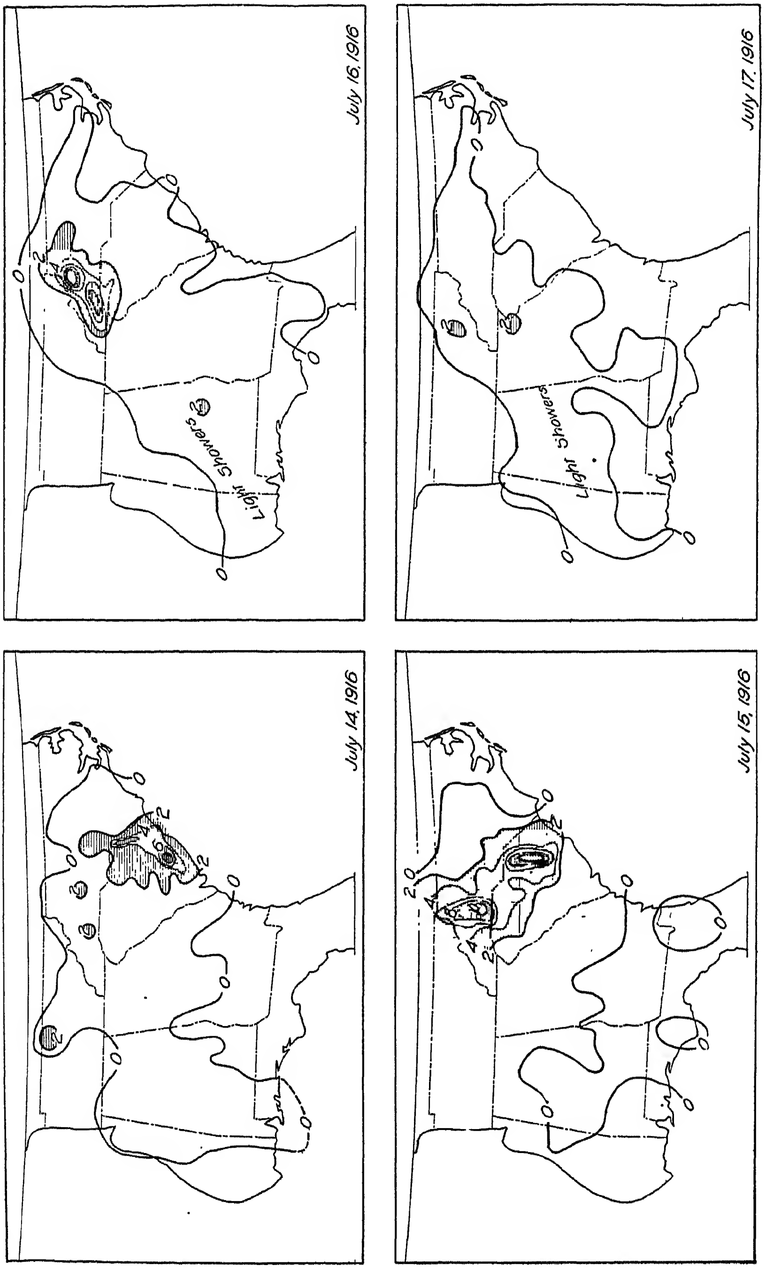

FIG. 95. Daily Precipitation in Southern Atlantic and East Gulf States, due to West Indian Hurricane (see page 176).

by Fig. 94, page 173, which show the weekly distribution of rainfall in Wisconsin for six consecutive weeks in May and June, 1907. All such maps are but the result or summation of individual rainstorms which occur during the period considered.

91. **Rainfall Accompanying West Indian Hurricanes.**—In most cases the rain accompanying the hurricanes from the West Indies falls

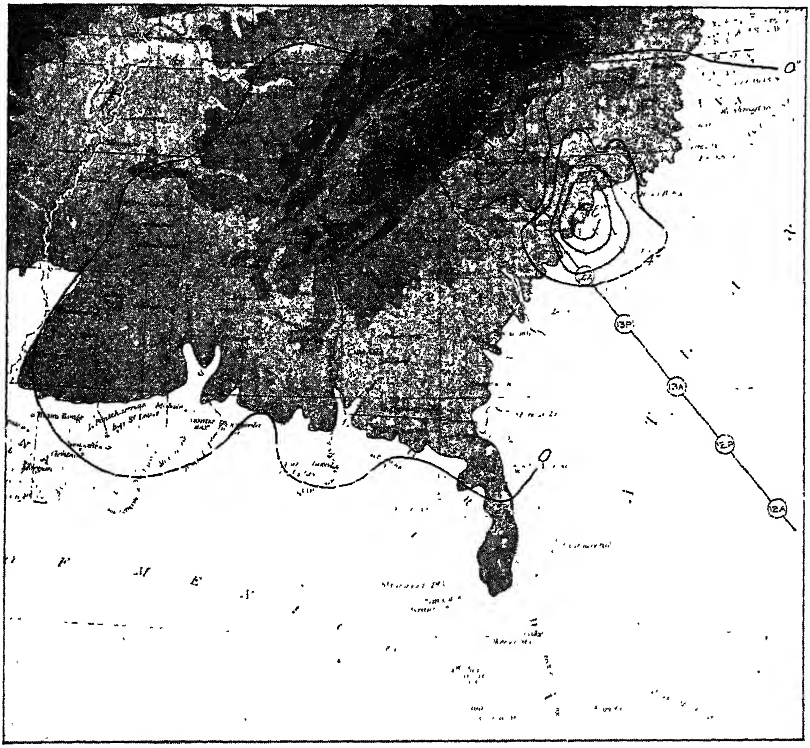

Fig. 96.—Precipitation due to West Indian Hurricane of July 14 to 18, 1916 (see page 176).

immediately adjoining the Coast near the point where the storm center reaches the land. Occasionally, however, the moisture is carried far inland and affects the country at some distance from the Coast. Two storms of this kind accompanied by rainfalls of considerable magnitude occurred in July, 1916. The first of these two storms entered from the Gulf of Mexico through Mississippi about July 5 and was dissipated when it encountered the southern span of the Alleghenies in South Carolina on July 13. This was followed by a record storm which

reached the coast of South Carolina on July 14, producing a heavy rainfall near the coast on that date, and proceeding to the northwest was also dissipated against the Southern Alleghenies on July 16 with an unusually intense rainfall. The progress of the storm for the four days, July 14, 15, 16 and 17, is shown in Fig. 95, and the combined rainfall for the entire storm is indicated on the relief map shown in Fig. 96, page 175. These maps show both cyclonic and orographic rainfall, resulting from the storm. The rainfall near Altapass North Carolina for the 24 hours on July 15 and 16 amounted to 22.22 inches,

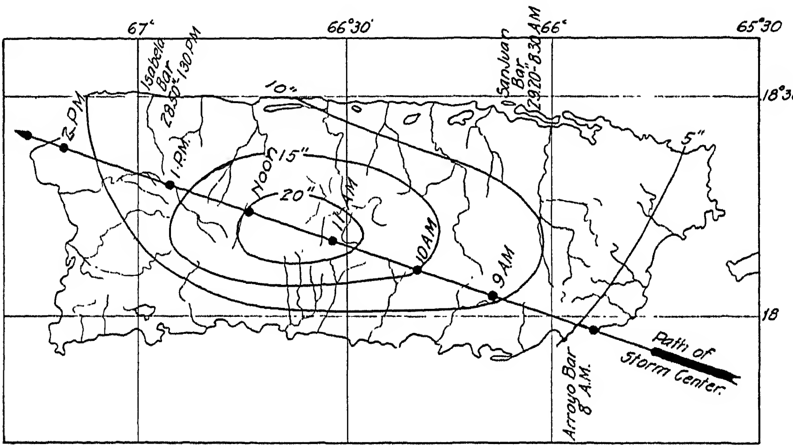

Fig. 97.—Rainfall on the Island of Porto Rico, resulting from the Hurricane of Aug. 5 to 9, 1884.

being one of the heaviest rains which has ever visited the United States.

The rainfall in the island of Porto Rico accompanying the hurricane of August 5-9, 1889, is shown on Fig. 97. Here the source of moisture is close at hand and the consequent rainfall is much greater than would commonly be the case over continental areas.

92. Rainfall Accompanying General Cyclonic Storms.—The general distribution of rainfall accompanying the cyclonic storms for March 20 to 23, 1913, inclusive has already been shown in Fig. 31, page 70, and the distribution for the four following days of March 24 to 27th, inclusive, is shown in Fig. 134, page 249. These storms led up to the extreme flood of March, 1913, in Indiana, Ohio, and the states farther east.

Figs. 98 and 99, pages 177 and 178, show the summation of the rain

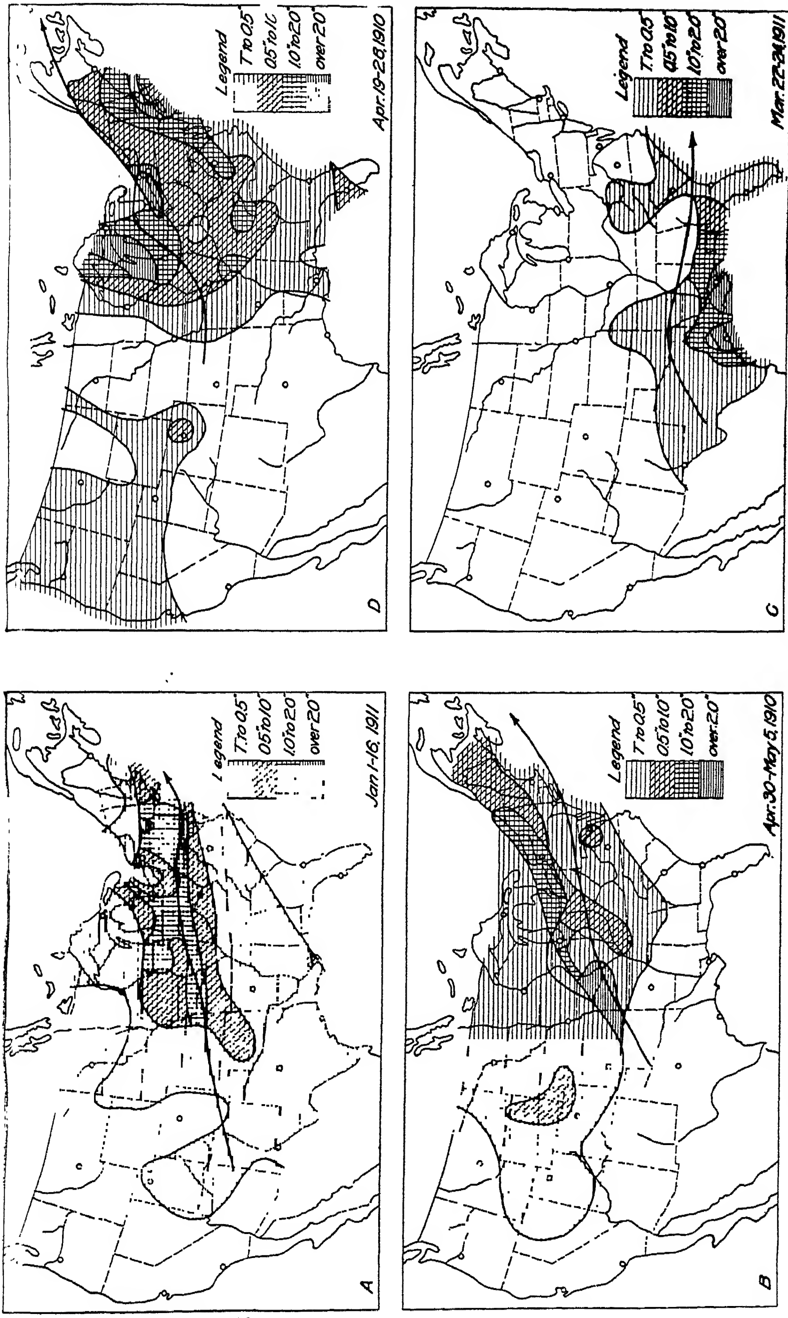

FIG. 98.—Rainfall Accompanying Certain General Cyclonic Storms[5] (see page 176).

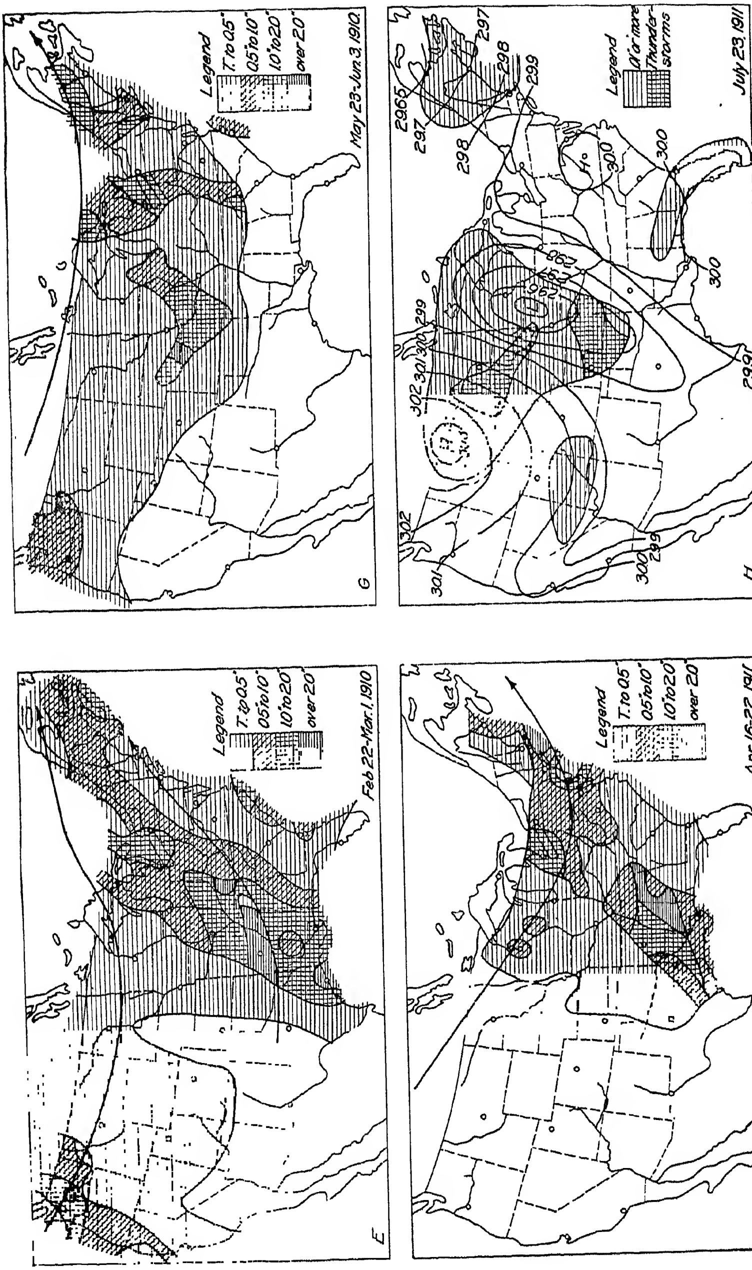

FIG. 99.—Rainfall Accompanying Certain General Cyclonic Storms [5] (see page 176).

accompanying various typical cyclonic storms.[5] Fig. 98, map A, shows the path of a cyclone of January 1-16, 1911, from Arizona on a central track with heavy precipitation on both sides of the path, showing the influence of moisture from the Great Lakes, the Atlantic and Gulf sources and the well watered interior.

Map B shows the path of the cyclone of April 30–May 5, 1910, of Texas origin following a central track. The heavy precipitation is to the north of its path and is evidently influenced by moisture from the Great Lakes region.

Map C shows the path of a cycline of March 22–24, 1911, originating in Texas and following the southern track. The heavy precipitation is on the south of the path and is evidently from moisture received from the Gulf and ocean.

Map D shows the path of the cyclone of April 19-28, 1910. There are two areas of precipitation separated by a rainless area. The path passes between two areas of heavy rainfall and the precipitation is evidently derived from the Great Lakes, Atlantic, Gulf and Pacific sources of moisture.

In Fig. 99 map E shows the path of the cyclones of Feb. 22–March 1, 1910. The northern cyclone caused precipitation from the Pacific northwest through the Great Lakes region. The second cyclone on the southern track caused the heavy precipitation from the Gulf up the Mississippi Valley to the Great Lakes region.

Map F shows the path of the cyclone of April 16-22, 1911, which entered the United States from Alberta and crossed on a northern course. Heavy precipitation followed on both sides of the path, evidently from the Great Lakes and Atlantic sources, and also to the southward, evidently from Gulf sources.

Map G shows the path of the cyclone of May 23-June 3, 1910, which path was wholly in Canada. The heavy precipitation was much broken and was apparently to the south of the path and from Pacific, Atlantic, Gulf, Great Lakes and interior sources.

Map H shows a typical case of the rain accompanying a thunderstorm and included in the general rain area of the cyclone of July 23, 1911, when the storm center was located over Iowa at 8:00 A. M. on July 23, 1911, Washington time.

93. **Thunder Storms.**—Many cyclonic storms are accompanied by only slight barometric gradients and the circulation of air is so weak

5 The Cyclonic Distribution of Rainfall, W. G. Reed. U. S. Weather Review, Oct. 1911.

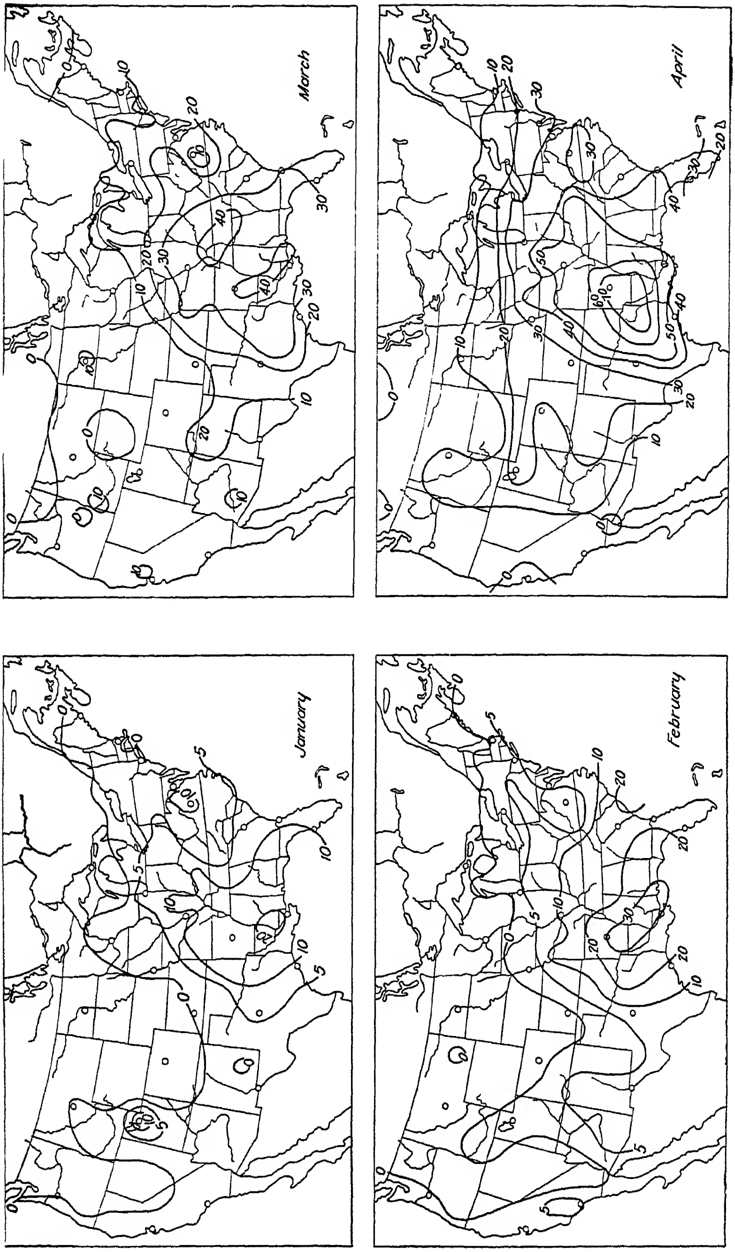

FIG. 100.—Total Number of Thunder Storms in each Month for the Period 1904–1913, Inclusive [6] (see page 183).

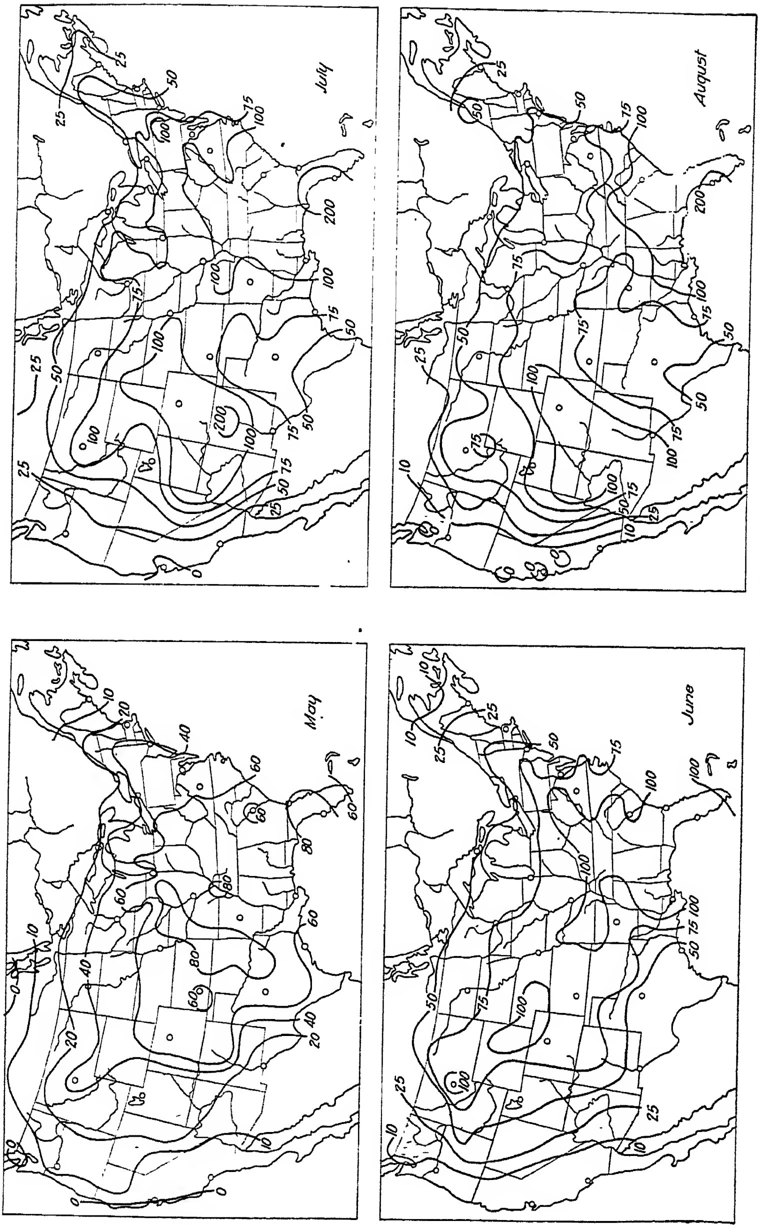

FIG. 101.—Total Number of Thunder Storms in each Month for the Period 1904–1913, Inclusive [6] (see page 183).

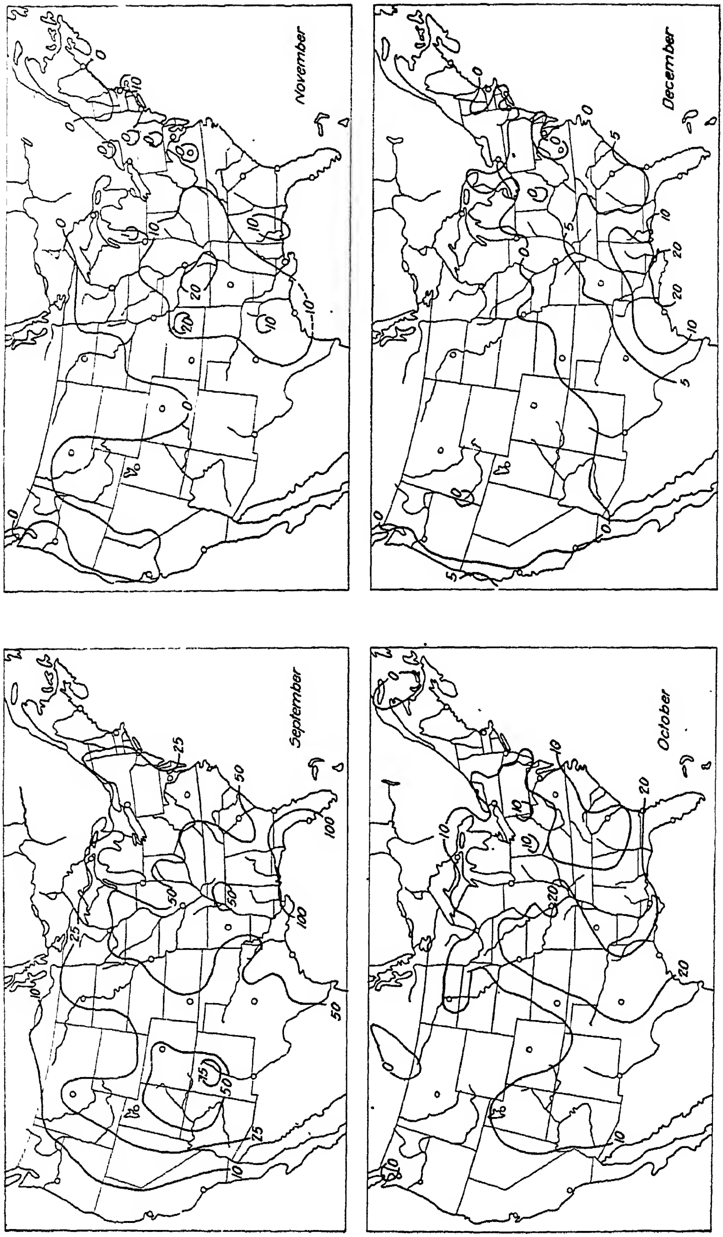

FIG. 102.—Total Number of Thunder Storms in each Month for the Period 1904–1913, Inclusive 6 (see page 183).

that smaller local secondary cyclones are frequently generated through local conditions. These are usually accompanied by electrical disturbances and heavy local rainfall and are known as thunder storms. Numerous similar local disturbances caused by intense convectional action are developed in the equatorial belt where the "afternoon thunder storm" is of almost daily occurrence.

In the United States these storms are of only occasional occurrence on the Pacific Coast but increase in number toward the east, and reach

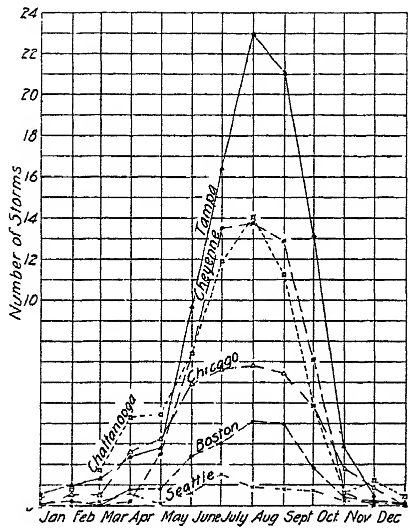

Fig. 103.—Average Number of Thunder Storms occurring Monthly at Various Stations for the Period 1904–1913, inclusive.[6]

a maximum in the extreme southeast. Their normal geographical and seasonal occurrence during the ten years 1904-1913 is shown by Figs. 100–102,[6] inclusive pages 180, 181 and 182. The normal variation in the occurrence of thunder storms from month to month during the year at widely scattered locations is shown in Fig. 103.

94. Annual Expectancy of Storms.—The expectancy of the annual occurrence of thunder storms is shown by Fig. 104 which is based on the average for the ten year period 1904-1913.

The approximate mean expectancy for cyclonic storms is illustrated by Fig. 105,[7] which is taken from Dunwoody's map summarizing the

[6] Distribution of Thunder Storms in the United States, Wm. H. Alexander, Monthly Weather Review, July, 1915.

[7] Bulletin A, U. S. Weather Bureau.

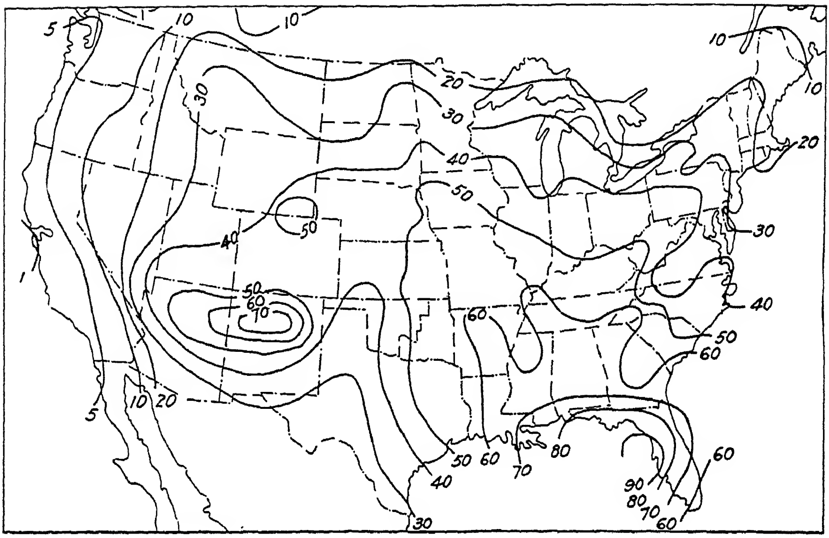

Fig. 104.—Average Annual Number of Thunder Storms in the United States based on observations from 1904 to 1913, inclusive (see page 183).

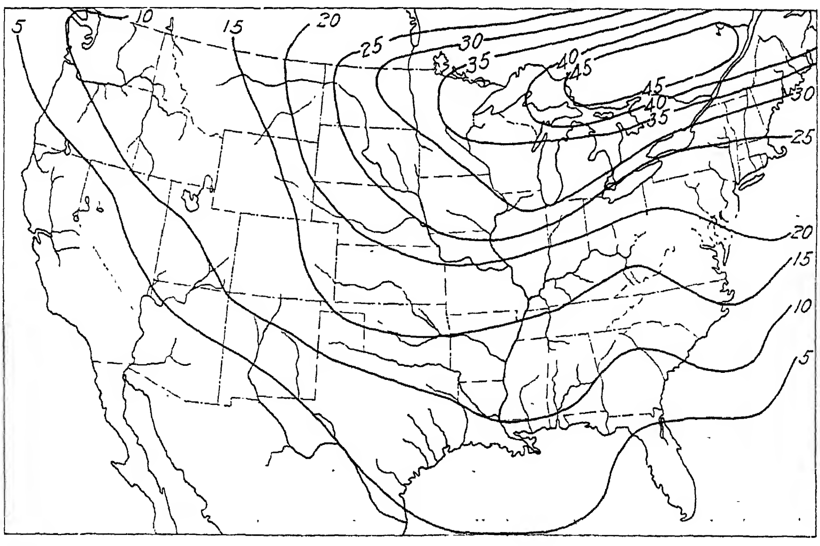

Fig. 105.—Annual Cyclonic Storm Frequency in the United States.

international meteorological observations for the period 1878-1887. Later information is contained in Supplement No. 1, U. S. Weather Review for 1914.

95. **Artificial Production of Rain.**—Various men have at different times declared that they could produce rainfall, usually by one of two methods, the discharge of explosives or the liberating of gases. This belief obtained such widespread acceptance that the United States Government undertook some experimental tests in 1892. Heavy charges of explosives were sent up into the interior of the clouds by means of kites and balloons, and there exploded, but without effect. The results obtained by various experimenters have not shown that any rain has fallen due to the agency of man. Similarly, the shooting of vortex rings, and the ringing of bells, as is done in France at the approach of hail storms, have no noticeable effect upon either the formation or path of the storm.

No one who appreciates the great atmospheric movements and dynamic changes that take place during rainstorms will believe that, by any process possible to man, any material control can be effected over such storm movements.

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CHAPTER VIII

RAINFALL MEASUREMENTS AND RECORDS

96. The Measurement of Precipitation, Instruments Used.—The ordinary rain gage as used by the United States Weather Bureau (Fig. 106,) consists of a galvanized iron cylindrical can, eight inches in diameter, the mouth of which is circular, beveled on the outside to

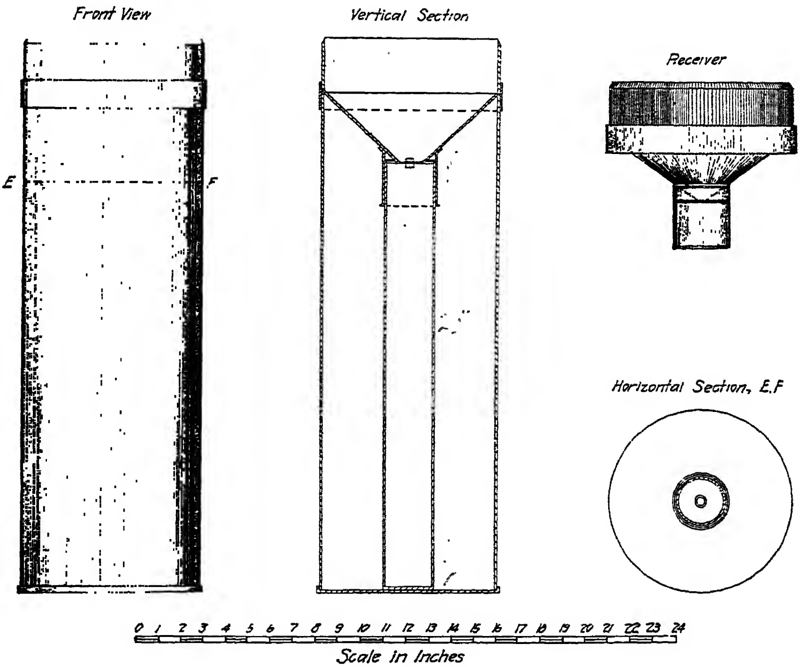

FIG. 106.—The Ordinary Form of Rain Gage

form a sharp edge. This receiver is funnel-shaped; the orifice leading from the funnel discharges into a brass cylindrical vessel, twenty inches in depth, the inside area of which is exactly one-tenth of the area of the receiver rim.

The depth of rain caught in this interior tube is measured by means of a wooden scale to tenths of an inch, thus measuring the rainfall caught in the gage to hundredths of an inch.

When used in measuring snowfall, the funnel-shaped entrance or rim of the tube is removed and the snow is caught directly in the outer can. The snow is then melted and the equivalent depth of water measured as in the case of rainfall A more satisfactory means of obtaining the amount of precipitation occurring in the snowfall is, however, to take several samples by inverting the can of the gage over a field of snow free from drifting or other wind effects, and melting the samples so taken.

Recording gages for measuring the quantity and rate of precipitation operate on various principles. The one perhaps in most general use in this country is the tipping-bucket gage. This gage is usually so constructed that a bucket becomes filled with 1/100 inch of rainfall, when it tips, brings another bucket into position, and records the movement upon a revolving drum.

"The collector, and, in some gages, the middle section, are separately detachable from the lower section of the inclosing case, in order to facilitate access to all the parts.

"The top section, called the receiver or collector, is made of a sharp-edged brass rim, accurately twelve inches in diameter inside, and provided with a funnel-shaped bottom and a small tube at the center so that all the water falling within the collector is conducted to a point directly over the center of the tipping-bucket bearings. The middle section is made of galvanized iron, with a hinged door, and the lower section, or reservoir, is also of galvanized iron, and provided with a brass stopcock at the bottom, for emptying the gage of water.

"A portion of the bucket frame and the tipping bucket is mounted on a detachable brass frame carried on brackets within the inclosing case. The brass bucket is divided by a central partition into two equal compartments.

"This bucket is mounted on suitable bearings placed below the center of gravity. Two stop pins on the side of the bucket limit the movement of the bucket on its axis and permit it to rest in one of two positions, in which either one or the other of the compartments of the bucket is presented in such a manner that it will receive and retain the water delivered through the funnel to the collector. The weight of the bucket and the position of its center of gravity have been so adjusted in relation to its supports that when one of the compartments has been charged with the quantity of water representing one one-hundredth of

an inch of rain in the twelve-inch gage, the bucket tips over upon its bearings, emptying the water from the one compartment, and at the same moment presenting the other compartment to receive the incoming water. The water thus delivered from the buckets is retained in the reservoir section for subsequent measurement in bulk.

"The automatic registration of each hundredth of an inch of rainfall, that is, each tip of the bucket, is effected by aid of an electrical circuit closer. A short sector is attached to the tipping bucket and when the bucket is at rest in either of its limiting positions the sector stands near to, but not in contact with, a pin on an insulated contact spring.

"In the act of tipping, after the bucket has moved a little, the sector makes contact with the pin, and rubs over it during the greater part of the subsequent motion. This effectually closes the electric circuit which is formed between the whole metallic framework, including the bucket, and the insulated spring. During the last portion of the tip of the bucket the sector slips off and moves a small distance away from the pin, thus opening the electric circuit, and also leaving the bucket perfectly free to tip with the next hundredth of an inch of rain."[1]

Other recording gages operate by floats or by weighing. In the case of the float type of gage, a float rises and falls with the increase and decrease of the water level within the receptacle and by so doing traces a line upon a revolving drum. In the Marvin weighing rain gage, the necessary vessel is kept in balance as the rain descends, by a counter-weight which is automatically moved by a magnet. Each impulse which is recorded on the sheet attached to the revolving drum, corresponds to 1/1000 of an inch of rainfall.

97. **Exposure of Rain Gages.**—The exposure of rain gages is a very important matter if accurate results are to be attained. The wind is the most serious disturbing cause, and when it blows against the gage it forms eddies near and above the mouth of the gage and frequently carries away the precipitation, especially when in the form of fine rain or snow and hence causes the gage to give erroneous results. Snow is frequently blown from the gage even after it has fallen into it, and the ordinary gage is of little value for the measurement of snowfall.

The stronger the wind the more it is apt to affect the catching of

[1] Measurement of Precipitation, C. F. Marvin. Circular E. Instrument Division, U. S. Weather Bureau.

precipitation, and two gages differently exposed are apt to register considerable differences even when located quite near each other.

"In a high location eddies of wind produced by walls of buildings divert rain that would otherwise fall in the gage. A gage near the edge of the roof, on the windward side of a building, shows less rainfall than one in the center of the roof. The vertical ascending current along the side of the wall extends slightly above the level of the roof, and part of the rain is carried away from the gage. In the center of a large, flat roof, at least sixty feet square, the rainfall collected by a gage does not differ materially from what is collected at the level of the ground. A gage on a plain with a tight board fence three feet high around it at a distance of three feet will collect six per cent more rain than without the fence. These differences are due entirely to wind currents.

"The rain gage should, if possible, be located in an open space unobstructed by trees, buildings or fences. Low bushes and fences, or walls that break the force of the wind in the vicinity of the gage are, however, beneficial, if at a distance not less than the height of the object. Gages should be exposed upon roofs of buildings only when better exposures are not available; and, when so located, the middle portion of a flat, unobstructed roof, generally gives the best results." [2]

98. Location of Rain Gages of the United States Weather Bureau.—The gages at the United States Weather Bureau stations in large cities are usually located on flat roofs. This altitude, together with the influence of surrounding buildings, has a considerable effect upon the air currents around the gage, and consequently the proportion of actual precipitation caught by the gage is more or less affected.

Alfred J. Henry [3] gives the following comparisons in rain gage registers on buildings and in the open areas:

St. Louis—The rain gage is located on the city post office, twenty feet from the edge of the roof and 100 feet above the street. The Forest Park rain gage is situated four miles west, in an open space seventy-five feet from any object and with its rim four feet above the ground.

A comparison of the records for five years (1891–1895) shows that the post office gage records greater precipitation in the winter, while the Park gage shows the greater amount in warm weather, especially

[2] Ibid.

[3] Rainfall of the United States, A. J. Henry. Report of the Chief of the Weather Bureau, 1896-7.

in May and June. On the yearly average, the park gage records a rainfall of about two inches—or five per cent greater than the post office gage.

Philadelphia—The Weather Bureau gage is located on the post office, 166 feet above the street. Mr. L. M. Dey made a comparison between the post office gage and a ground gage located three miles east. An average covering six years shows that the ground gage registered three inches or eight per cent per year more than the post office gage.

New York—Weather Bureau gage is situated on the roof of a building 150 feet above the street. A comparison is made with the records of the Central Park gage, which is sixty-three feet above the ground. Covering a period of twenty years, shows that the Weather Bureau gage registers 2.17 inches or about 5 per cent greater than the Central Park gage.

These variations are probably due to the effect of local air currents in carrying a greater or less amount of the falling rain out of the mouth of the gage.

99. **The Effect of Wind.**—The value of rainfall records for hydrological, agricultural or meteorological studies depends upon the accuracy with which they represent the actual occurrence of rainfall over the area under investigation. Any single gage can measure only the precipitation occurring within its own areas, and its application to a wider area must be on the assumption that the precipitation is uniform over the area to which the data are applied or that the rainfall varies uniformly between gages when the data from two or more gages are utilized.

It is well understood that local topography and the position of the gage with reference to the height above the surface of the ground and with further reference to trees, buildings or other objects, together with the relative direction and amount of the wind, may produce great differences in the amount of rainfall collected by a series of gages.

The difference in the amount of rainfall which will be collected by gages exposed at different heights above the surface of the ground has been conclusively shown to be due to wind currents. Jerome explained this phenomena as follows: [4]

"To show clearly the nature of this effect we may imagine the stream of air M N (Fig. 107, page 192) to be suddenly contracted at B C to

[4] See Philosophical Magazine, 1861; also The Effects of Wind Currents on Rainfall. G. E. Curtis, Signal Service Notes, No. 16, 1884.

half its previous thickness, so that of course, it must there commence to move with double velocity. At A D the stream dilates to its original size, and of course recovers its first velocity. The course of equidistant rain drops falling into wind under such imaginary circumstances would be represented by the oblique lines, and it is obvious that less rain would fall in the windward part of the contracted space than elsewhere."

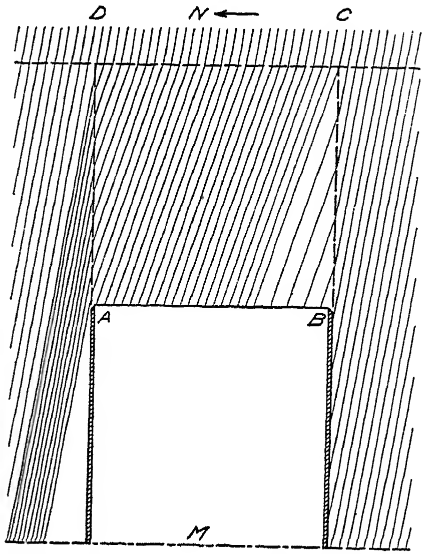

Fig. 107.—Effect of Wind upon the Catchment of the Rain Gage (See page 191).

For the same reason, with rain gages located on a roof the gages to the leeward will catch more rain than those to the windward, and with the location of gages on a mountain top or in other positions where the direction or intensity of the wind may seriously affect the catchment of the rain, considerable difference will be found between gages set in the same vicinity.[4]

The difference in the measurement of rainfall by various gages is often marked. In the winter of 1852–3 there was established at Rothamstead Experimental Station, in England, a rectangular rain gage 6 feet wide by 7 feet 3.12 inches in length, having an area of one-thousandth of an acre.[5] This large gage was established partially for the

[5] Amount and Composition of Rain and Drainage Waters Collected at Rothamstead, by Lawes, Gilbert & Warington, Jour. Royal Agric. Soc. of England. Vol. 17, 1881, p. 224.

accurate determination of rainfall and partially to allow the collection of the rain in sufficient quantities for chemical analysis. The surface of the gage was two feet above the level of the surrounding ground. Closely adjoining this gage and at the same elevation above the ground surface was placed an ordinary rain gage consisting of circular copper funnel 5 inches in diameter, delivering into receptacle enclosed in a metallic cylinder. Observations for 28 years showed that the small gage indicated a distinctly less average quantity of rainfall than the larger gage. The means of the 28 years readings (1853–80) of both the large and small gages are shown in Table 14.

TABLE 14.

Comparison of the Large and Small Rain Gages.
(Means of 28 Years)

	Mean Monthly Rainfall		*Defficiency of Small Gage*	
	Large Gage Inches	Small Gage Inches	Actual Inches	Percent
January	2.500	2.263	0.327	12.6
February	1.728	1.508	0.220	12.7
March	1.693	1.399	0.294	17.4
April	2.008	1.803	0.205	10.2
May	2.329	2.149	0.180	7.7
June	2.451	2.272	0.179	7.3
July	2.704	2.533	0.171	6.3
August	2.643	2.440	0.203	7.7
September	2.638	2.403	0.235	8.9
October	3.089	2.784	0.305	9.9
November	2.345	2.113	0.232	9.9
December	2.084	1.861	0.223	10.7
Total for Year	28.302	25.528	2.774	9.8

Some of the causes contributing to this difference were manifest, for example: a heavy snowfall was much better retained by the large gage than by the small one; the deposits of mist, dew and frost were also distinctly greater with the large gage. The effect of winds on the smaller gage was probably the main contributing factor for other differences.

100. Records of Rainfall of the United States.—The sources of rainfall data in the United States, so far as generally available, may be found in the following publications:

Abstracts of all the records of observations of rainfall which have been made from the early settlement of the country down to the close of the year 1866, so far as they could be obtained, were contained in Smithsonian Contribution to Knowledge No. 222, published in 1874, and entitled "Table and Result of the Precipitation and Snow in the United States," by C. A. Schott.

In 1872, the United States Signal Service began the publication of the results of the observations made at various army stations by the post surgeons of the United States Army in the "Monthly Weather Review," including in this publication various reports of the State Weather Services and voluntary observers, Canadian stations, and various stations maintained by the Central Pacific Railway Company, the Hydrologic office, Navy Department, and the New York Herald Weather Service.

Upon the establishment of the U. S. Department of Agriculture in 1891, the Weather Bureau was organized as a branch of this service, and the Weather Review has since been published by this Bureau. In general this Review has summarized the current data received from both land stations and ocean vessels, as well as from several European and Asiatic stations, but did not include the daily rainfall observations until July, 1909, when it was enlarged to embody the daily observations at each of the weather stations, including also various additional data secured by an association with various other bureaus of the government whereby the latter assisted in the collection of data not hitherto available from the various other localities. This continued until January, 1914, when the publication of rainfall data was dropped from the Review.

From the early '90's to 1909, the climate and crop service of many of the states published each month in various forms the rainfall and other climatological data for the particular state. In 1909, the state work was largely discontinued on account of the publication of this work in the Weather Review.

The state climate and crop service reports were issued in small editions, sometimes the early report being published only in a newspaper at the Section Center. They are not generally available, although usually complete files are found at the office of the Weather Bureau Section Center where duplicates for some special months and years may occasionally be obtained. These reports, more or less complete, can usually be found at the principal offices of the United States Weather Bureau.

Since January, 1914, the Weather Bureau has published, under the head of "Climatological Data," the daily rainfall data of various sections. These sections follow in general the geographic division of the states; the exceptions are that the Maryland section includes Delaware and the District of Columbia, and the New England section comprises the New England States. These reports are printed at the sev-

eral Section Centers and are generally available to those interested in the local sections. A limited edition, including all the various sections, is assembled and bound at the Washington office for Service use and exchange.

The Weather Bureau has also published a summary of the monthly rainfall data for the United States in 106 sections. This summary is a combination of all the available rainfall data since 1870 when the general Meteorological Service of the United States was first established. Most of these sections are brought up to include the year 1908, while others, published later, include the year 1909. The summary is bound in two volumes, known as Bulletin W.

The report of the Chief of the United States Weather Bureau, from the year 1891 to date, includes the annual and monthly rainfall records and other climatological data.

101. **Dependability of Precipitation Records.**—The dependability of many ancient rainfall records, taken in unknown ways and under unknown conditions, are open to serious question. From that which has been previously stated, it is obvious that many of the present records are also subject to more or less error. Subject, as they are, to considerable variations, it would seem unwise to use great refinement in the calculations of rainfall, and in recording rainfall one decimal place is probably the ultimate limit of possible accuracy. It should also be recognized that the rainfall maps, showing lines or belts of equal rainfall, are only approximately correct, and that it would be impossible to show by such lines small differences in annual rainfall of less than two or three inches.

When considering the occurrence of rainfall in particular storms, the conditions are further complicated by the fact that not all the stations reporting furnish data taken at the same time. Most of the stations read the accumulated daily precipitation at 8 P. M., Washington time. The principal Weather Bureau Stations record the rainfall that occurs from midnight to midnight, while at a number of river stations the rainfall is recorded at 8 A. M. The consequence is that a rainstorm which occurs at essentially the same time at two different stations is frequently recorded as occurring on different days.

Most of the principal Weather Bureau Stations are located in cities, and observations are made on top of high buildings where air currents, frequently greatly modified and controlled by other buildings in the immediate vicinity, seriously affect the measured rainfall. It is probably true that the rainfall records from few of the principal sta-

tions in the United States fairly represent the local rainfall within several per cent. Not only is the record of rainfall probably inaccurate, but the conditions from year to year are apt to change through changes both in the construction or arrangement of surrounding buildings and in the changes made necessary by the changes in location of the Weather Bureau offices. For example, the Chicago office of the Weather Bureau occupied the Major Block (elevation ninety-three feet) from June 8, 1873 to December 31, 1886; the Chicago Opera House building (elevation 132 feet) from Jan. 1, 1887, to Jan. 31, 1890; the Auditorium Tower (elevation 238 feet) from Feb. 1, 1891, to June 30, 1905, and the Federal building (elevation 133 feet) from July 1, 1905, to date. The exposure of the rain gages at these various locations leads to the conclusion that the records are not strictly comparative, but are modified by the influence of the local condition.[6]

It is evident that, as many rainstorms have definite limits and do not shade off gradually to nothing, as is shown by the clear lines of demarcation sometimes left in the dust by passing showers, there may be considerable legitimate difference in the readings of rain gages which are placed close together, in addition to such differences as may be due to the wind. Hellmann found that monthly totals of gages only 1,500 feet apart would differ by five per cent, while for individual storms they might differ even 100 per cent., and considerable difference in the annual rainfall must be expected in gages even five miles apart.[7] The above may account to some extent for the differences noted in the gages at St. Louis, Philadelphia and New York, mentioned in Sec. 98. The matter of securing correct rainfall records has not received the attention that its importance demands, and it is to be hoped that the U. S. Weather Bureau, which is doing such valuable service in many ways, will give more attention to this matter which is of great importance in hydrological investigations.

102. Estimating Rainfall on any Area.—From the previous discussion it is evident that in estimating the amount of rain which has fallen on a given drainage area during a given period, much doubt will exist as to the accuracy of the results which may be obtained. Rainfall stations are often widely separated and undoubtedly their records do not always fairly represent the rain falling on intervening territory (see Sec. 121, page 245 and the records of Weather Bureau Stations) for

[6] The Weather and Climate of Chicago, H. J. Cox and J. Armington Bulletin No. 4, Geographical Society of Chicago, p. 152.

[7] Descriptive Meteorology, W. L. Moore, p. 209.

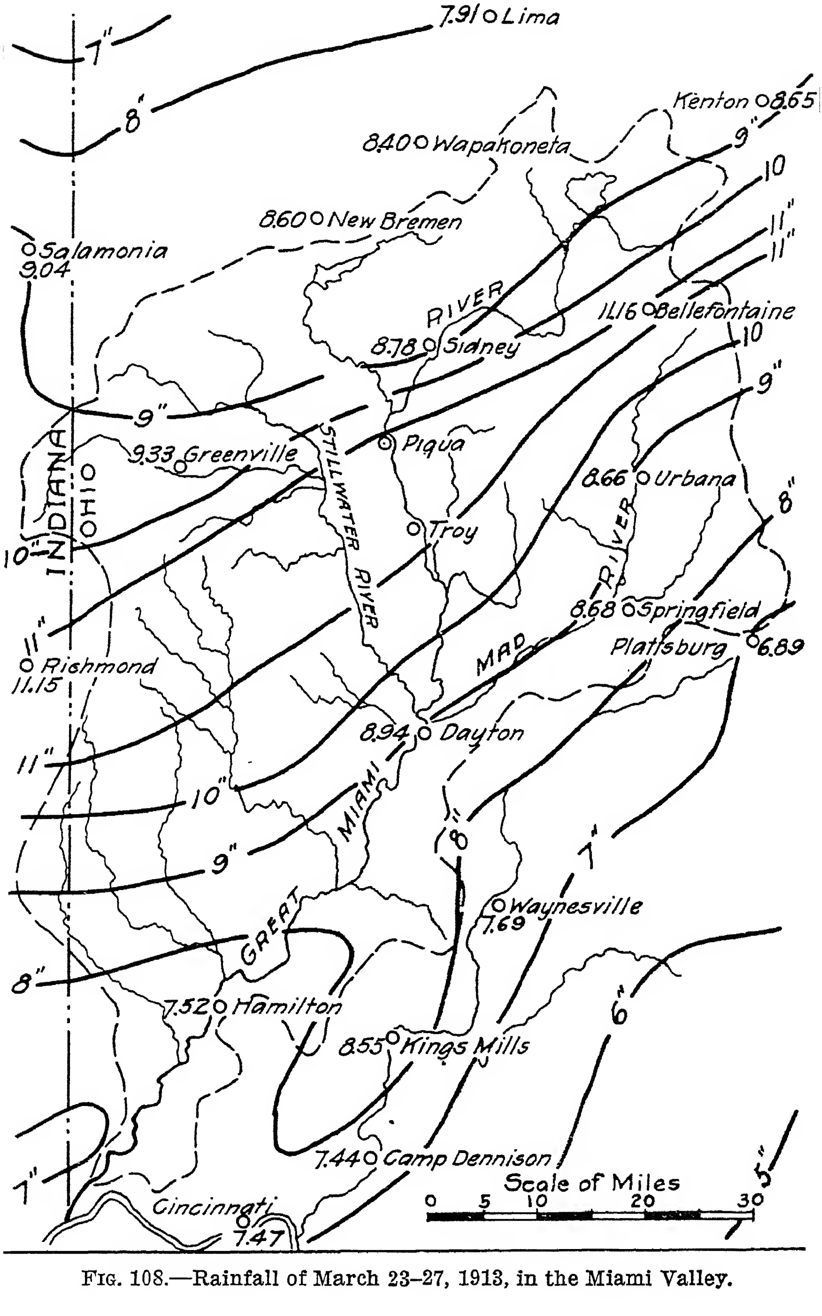

FIG. 108.—Rainfall of March 23–27, 1913, in the Miami Valley.

single storms or for short periods are at the best only roughly approximate as to the rain falling on the area between stations, and approximate for the annual rainfalls. As the number of stations increases on and closely adjoining a drainage area, the accuracy of the average records as representing the average rainfall on the intervening area will increase, provided the stations are fairly well distributed. In making such estimates the records of rainfall stations bunched on the area should be segregated and averaged and given only such weight as will represent a fairly uniform distribution of stations compared with the stations on the remaining area. The most accurate results can usually be obtained by drawing isohyetal lines on the rainfall map, determining the area of a given density of rainfall by means of a planimeter, and then calculating the total as the weighted average of areas with given densities of rainfall. For example, in the rainfall of March 23–27, 1913, on the Miami River drainage area (Fig. 108, p. 197), the average of the rainfall at all stations (omitting Lima, Salamonia and Camp Dennison) is 9.01 inches, while the weighted average based on the area between the isohyetal lines is 9.5 inches. In this case the stations are fairly well distributed. In many cases the distribution of stations would be much more unsatisfactory and the error in the estimate much greater.

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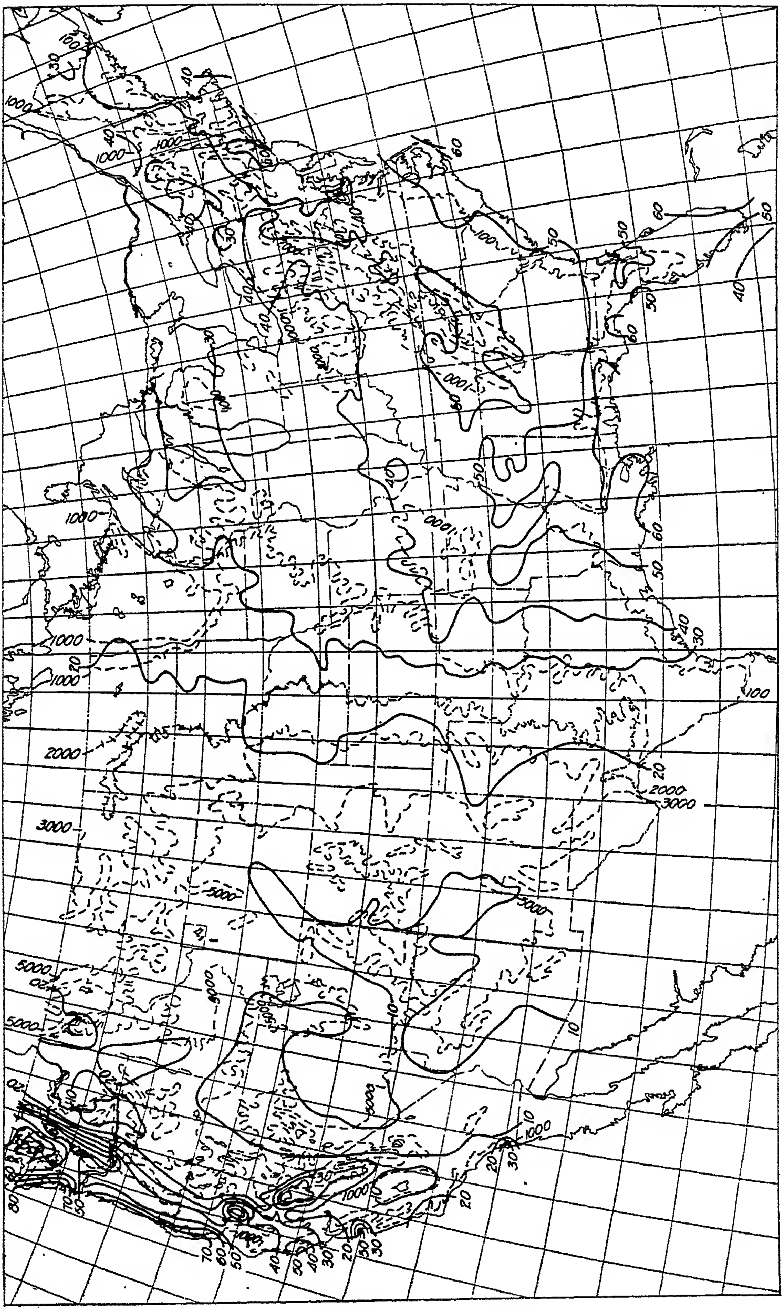
CHAPTER IX

ANNUAL RAINFALL IN THE UNITED STATES AND ITS VARIATION

103. **Quantity and Distribution of Average Annual Rainfall.**— The quantity of the average annual rainfall in the United States varies greatly at different points, as will be seen from Fig. 109, page 201, which shows the distribution of the average annual rainfall based on average local rainfalls to June 1, 1916. From this map it will be noted that "from the great plains westward the lines of equal rainfall are, approximately, north and south. In the Southern States, east of Texas, they are approximately parallel to the Gulf coast. In the Eastern States they are approximately parallel to the Atlantic coast. In the Lake region, while they approach parallelism to the parallels of latitude, yet there are some variations, evidently due to the effects of these great bodies of fresh water and their temperature at different seasons of the year. In the vicinity of Cape Hatteras and on the Peninsula of Florida, other influences come into play, modifying the direction of the lines of equal rainfall. Cape Hatteras is the point of highest rainfall along the Atlantic coast, due, undoubtedly, to the seasonal winds which pass at sea and reach, more or less, this prominent point. On the Peninsula of Florida we approach the tropical region and approximate the laws of tropical rainfall. East of the ninety-fifth meridian the rainfall decreases as the latitude increases. West of that in general the lines run north and south." [1]

It may be observed that the rainfall apparently decreases with increase in elevation: This is very noticeable in passing along, for instance, the parallel of latitude 40°. The annual rainfall on the coast of New Jersey ranges from 40 to 50 inches. As we pass westward we come to the area where the rainfall is about 40 inches. This rainfall continues along the parallel until the vicinity of the Mississippi River is reached, when it decreases with the comparatively rapid ascent of the slope to the great plains. By the time Kansas is reached the annual rainfall has fallen to 30 inches; in western Kansas it is only 20 inches, and in passing the boundary of western Kansas we pass the annual rainfall line of 15 inches.

[1] Bulletin C, Weather Bureau, page 13.



al Map S g'

These conditions of rainfall are, however, undoubtedly due to distance from sources of vapor origin instead of to altitude, which, as shown in another place, with other things being equal, increases the rainfall rather than diminishes it.

In general therefore, the distribution of the mean anuual rainfall is explainable on the basis of the factors already discussed. Among the mountains, on the Pacific Coast and in the great interior basin the phenomena of precipitation are more complex and the reasons for differences in distribution not so evident, on account of topographical irregularities.

Even in portions of the country where the topographical relief is apparently not sufficient to modify the quantity of rainfall, considerable differences sometimes occur within short distances for which there seems no adequate explanation. For example, Mather and Meadow Valley, Wisconsin, are about 6.5 miles apart but the rainfall of Mather exceeds that at Meadow Valley by about 4 inches per year, which is fairly uniform for the six years of parallel records:

Year	1912	1913	1914	1915	1916	1917	Mean
Mather	33.45	37.43	32.38	31.51	32.39	30.64	32.96
Meadow Valley	30.27	30.79	27.77	31.49	27.46	25.59	28.89
Difference	3.18	6.64	4.61	.02	4.93	5.05	4.07

Appleton and Menasha, Wisconsin, are located about 7 miles apart but there is a mean difference in the annual rainfall at these two stations of about 3.4 inches, the Appleton rainfall averaging higher. Here, however, the differences are not constant as will be noted from the parallel records for the last eight years:

Year	1910	1911	1912	1913	1914	1915	1916	1917	Mean
Appleton	24.43	36.65	30.54	37.08	35.82	28.97	33.95	28.00	31.93
Menasha	23.45	32.30	31.55	29.66	30.29	29.11	28.74	25.09	21.57
Difference	.98	4.35	—1.01	7.42	5.53	—.14	5.21	2.91	3.36

It is readily understood that extreme storms will frequently give rise to great differences in rainfall at stations closely adjoining, but fortuitous circumstances will seldom tend toward one direction for any considerable term of years, and when such tendency is displayed it would seem to indicate some constant influence which affects the phenomena in the direction noted.

104. **Variation in Annual Precipitation.**—While the causes that produce the normal local rainfall are difficult to determine, the causes which produce the variations that occur in the total annual precipitation and in its distribution are still more difficult to trace. The in-

vestigator must confine himself largely to a study of the actual variation and the actual distribution in endeavoring to determine their limits and the effects due to them. The map of average annual rainfall is of value for only a general view of the subject. Even the study of the general rainfall map from year to year gives only limited information (see Figs. 110 and 111, page 204); although the variations in such maps begin to show the large departures from average conditions that occur locally. The average or mean conditions of precipitation are of only general importance. The extreme conditions are those most directly modifying runoff and which seriously affect hydraulic problems. A water supply, for whatever purpose, should be constant in quantity or vary only as the demand for water varies, otherwise continuous service will be interrupted or must depend on other provisions; hence the occurrence of minimum conditions will largely modify the nature and extent of works intended to conserve and equalize such supplies. The maximum precipitation resulting in extreme flood flows must, on the other hand, modify works intended for escapement and flood protection.

The two maps of annual rainfall show a considerable variation in the rainfall for the years 1906 and 1904. They show, however, a general similarity in distribution even while great local differences are discernable. As a general rule it is found that great variations in rainfall are more or less local in character, and while it may be very dry in one part of the United States, it is apt to be unusually wet in some other portions. In general, wet and dry periods may occur in areas of considerable magnitude, but the great differences are more readily discernable when smaller areas are compared.

105. Variation in Annual Rainfall in Limited Areas.—For special purposes, a detail study of the local variations from the average conditions is necessary. Great variations take place in the annual rainfall of every locality. Sometimes the annual rainfall will be considerably below the average for a series of years, and then for a number of years the average may be considerably exceeded. No general law seems to hold, however, in regard to this distribution and the variation seems to occur either without law or by reason of laws so complicated as to defy determination. The variations in the distribution of the annual rainfall in the State of Wisconsin for 24 years are shown by Figs. 112 and 113, pages 205 and 206. From these maps it can clearly be seen how greatly the distribution of rainfall throughout the

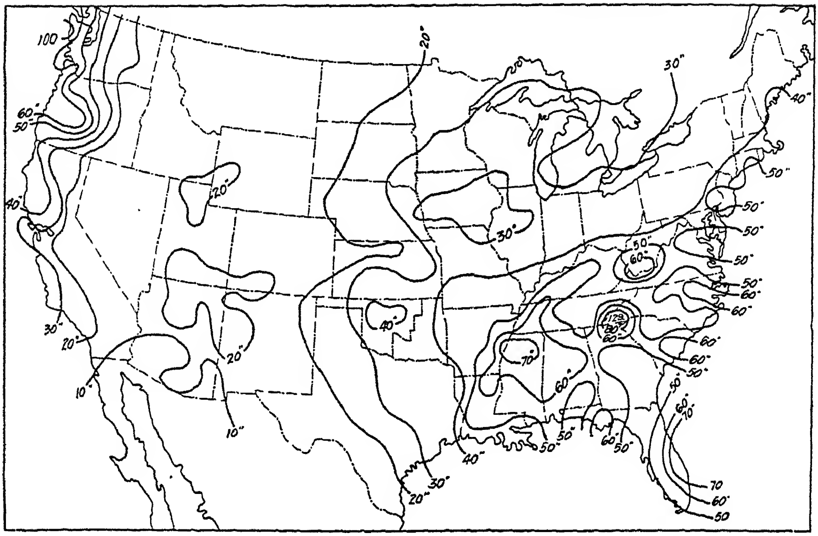


FIG. 110.—Annual Rainfall 1906.

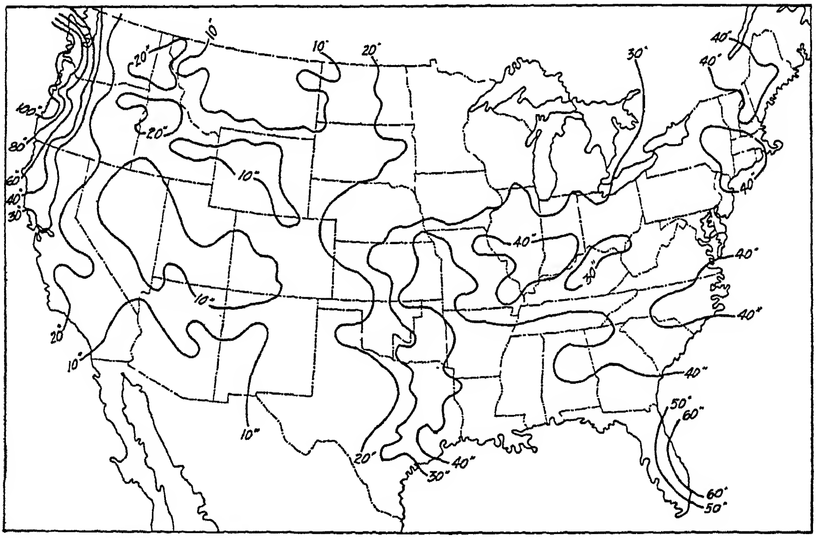


FIG. 111.—Annual Rainfall 1904.

state differs in different years from the average annual rainfall as shown by Fig. 114. Even in the State of Wisconsin there are few, if any, years when the rainfall in the entire state is uniformly very high or very

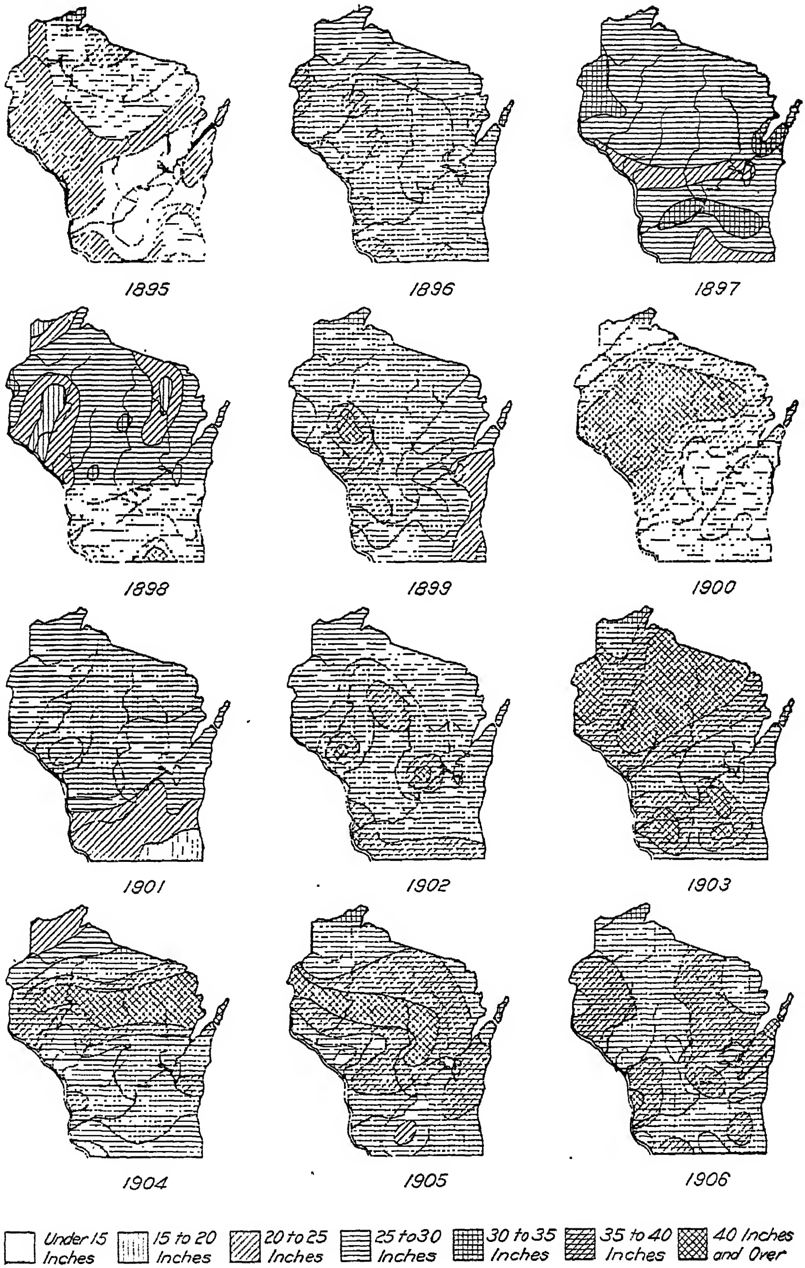


FIG. 112.—Annual Rainfall in Wisconsin (see page 204).

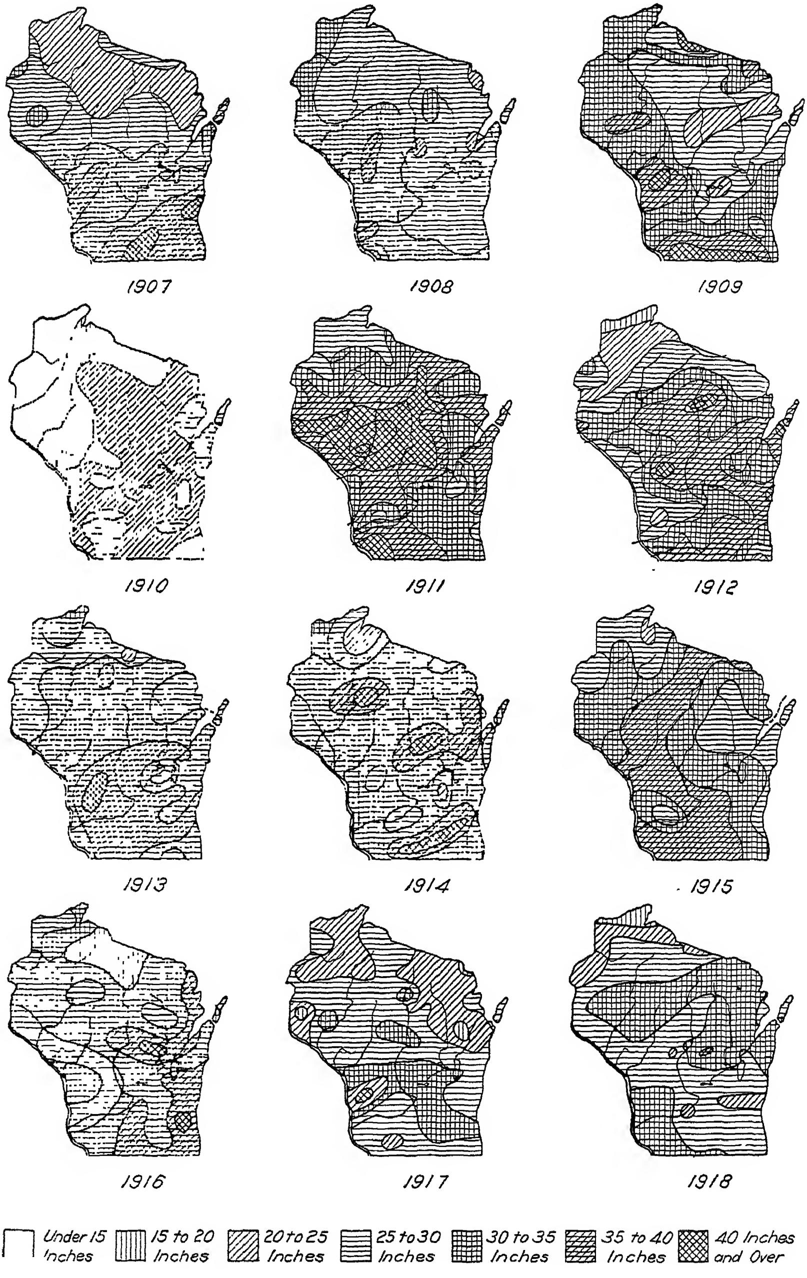


FIG. 113.—Annual Rainfall in Wisconsin (see page 204).

low. The year 1910 (Fig. 113) was perhaps the year of lowest average rainfall, and the year 1903 (Fig. 112) the year of highest average rainfall. Fig 114 indicates that on the average the rainfall is fairly well

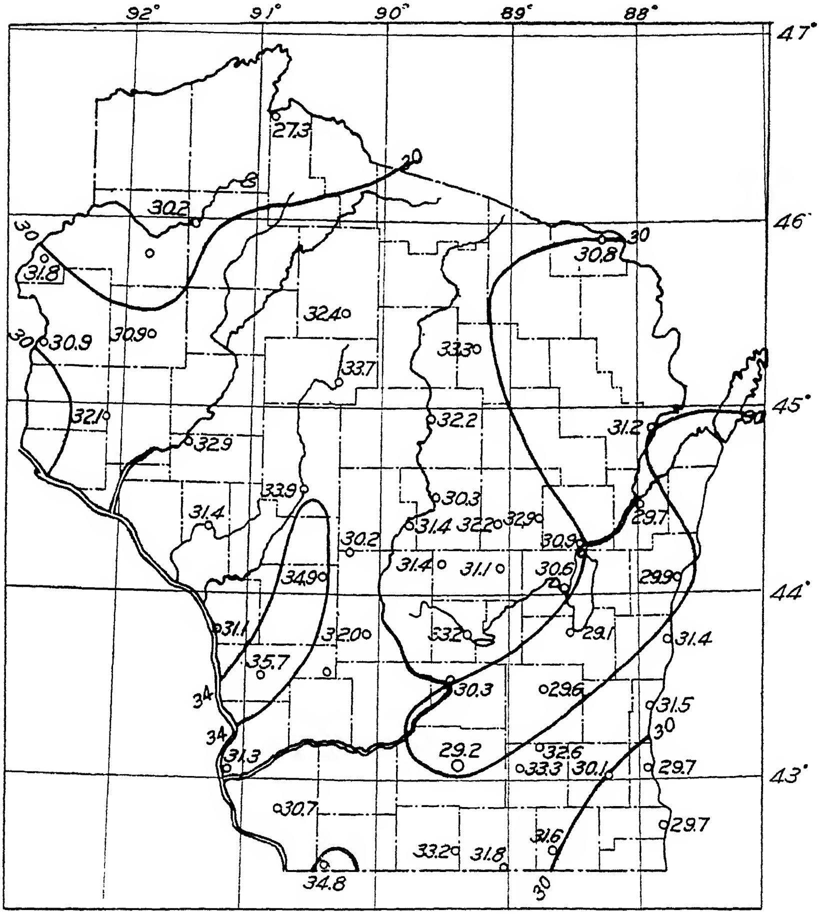


Fig. 114.—Mean Annual Rainfall in Wisconsin, 1895–1918.

distributed and gives no indication of the great variations that actually obtain over areas of considerable size, as indicated by the maps of Figs. 112 and 113. Even these maps fail to indicate the great range of variation that takes place in more limited localities.

106. Variation in Local Annual Rainfall.—The variation in annual rainfall at various selected stations in the United States is shown in Figs. 115 and 116, pages 209 and 210, on which are also indicated

the means for each station. From this diagram the annual variation and the relation of such variation to the mean are clearly shown.

Some idea of the limiting conditions, and the average relations of extremely dry and extremely wet periods can also be determined from this diagram.

The question is frequently raised as to whether or not the total annual rainfall is increasing or decreasing, and many believe that the removal of forests has a detrimental effect and that the cultivation of ground, and especially irrigation, has increased the annual rainfall. Meteorologists are generally of the opinion that the causes which influence rainfall are too great and too far-reaching to be modified by any possible works of man, and the records seem to bear out this opinion.

In the investigation of the tendencies of annual rainfall or other similar varying phenomena to follow harmonic laws, the tendencies may frequently be studied to advantage by platting the means for five or ten-year periods or the progressive means calculated by one of the usual formulas. By any of these methods erratic occurrences are eliminated and any gradual change is more clearly developed.

In Figs. 117 and 118, pages 211 and 213 the progressive means have been calculated by the formula

$$c' = \frac{a + 4b + 6c + 4d + e}{16}$$

in which a, b, c, d, and e are the annual rainfall for successive years and c′ is the progressive mean for the middle year in which the actual rainfall was c. In Fig. 117 each locality was represented by the average of two or more stations, and to these averages the above method was applied. The figure shows the progressive mean of the rainfall in various sections of the United States for a considerable period of years, and illustrates the fact that in every section the rainfall is subject to considerable variations. From this diagram it is easily seen that if the rainfall record for only a limited series of years is considered, conclusions might readily be drawn from almost every section that the rainfall is increasing or decreasing, according to the data selected. For example, from the diagram of the rainfall of New England, a continued increase is noted for the year 1838, when the progressive mean was 8.8 inches below the mean for the period, to the year 1890 when the progressive mean was 7.5 inches above the mean for the period; while from 1890 to 1907 there is a continued decrease

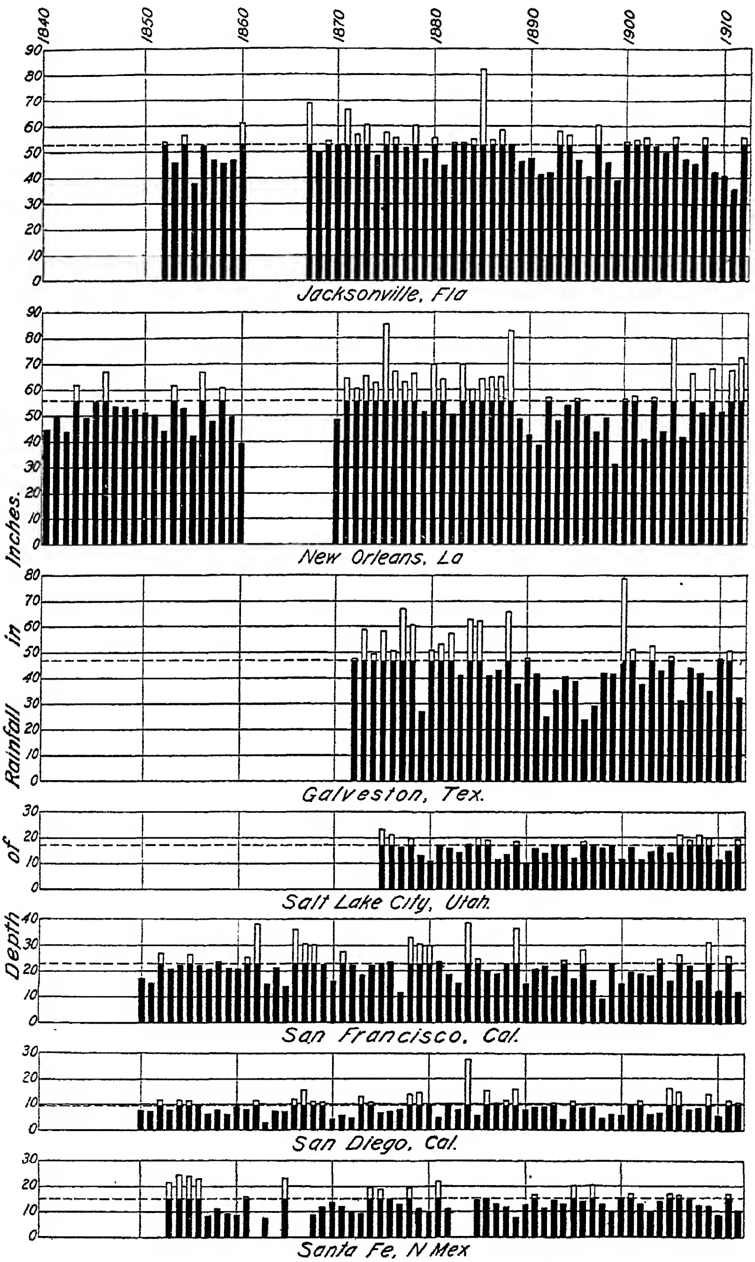


FIG. 115.—Variation in Annual Rainfall at Various Stations (see page 207).

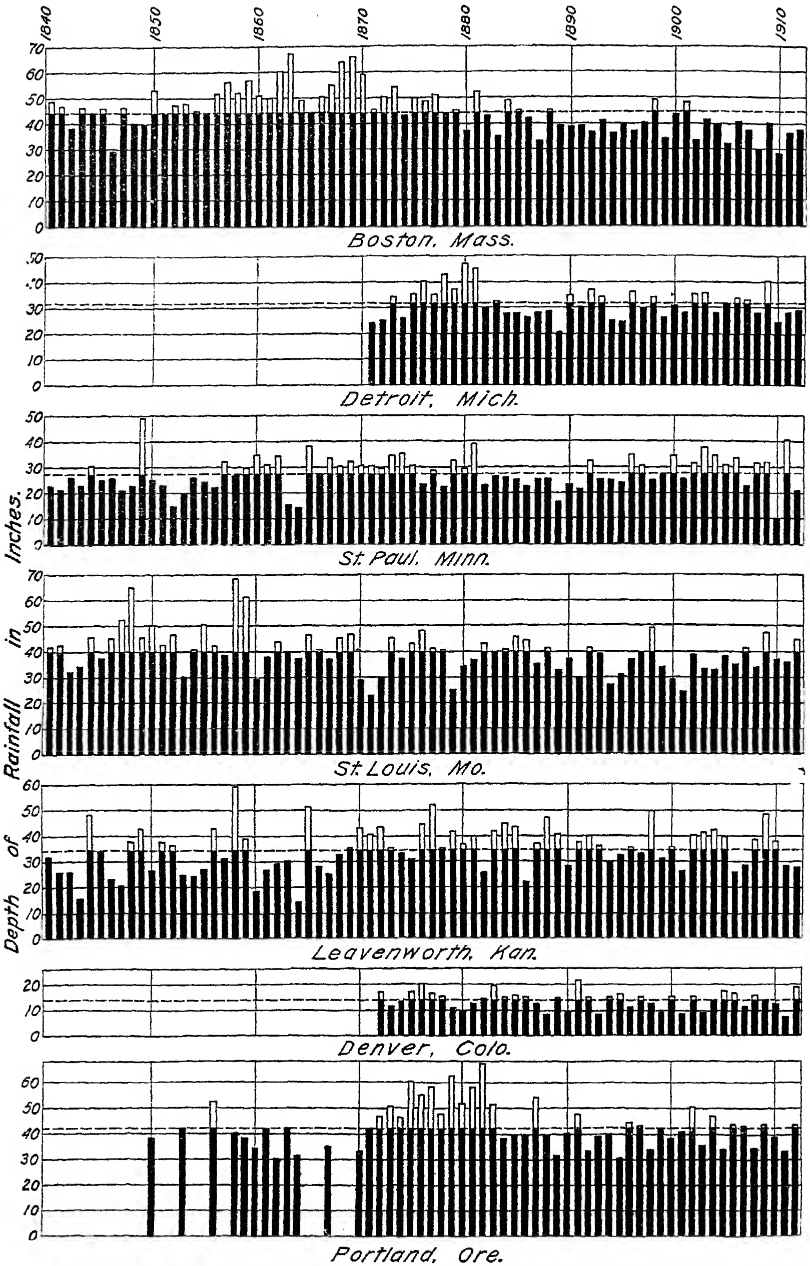


FIG. 116.—Variation in Annual Rainfall at Various Stations (see page 207).

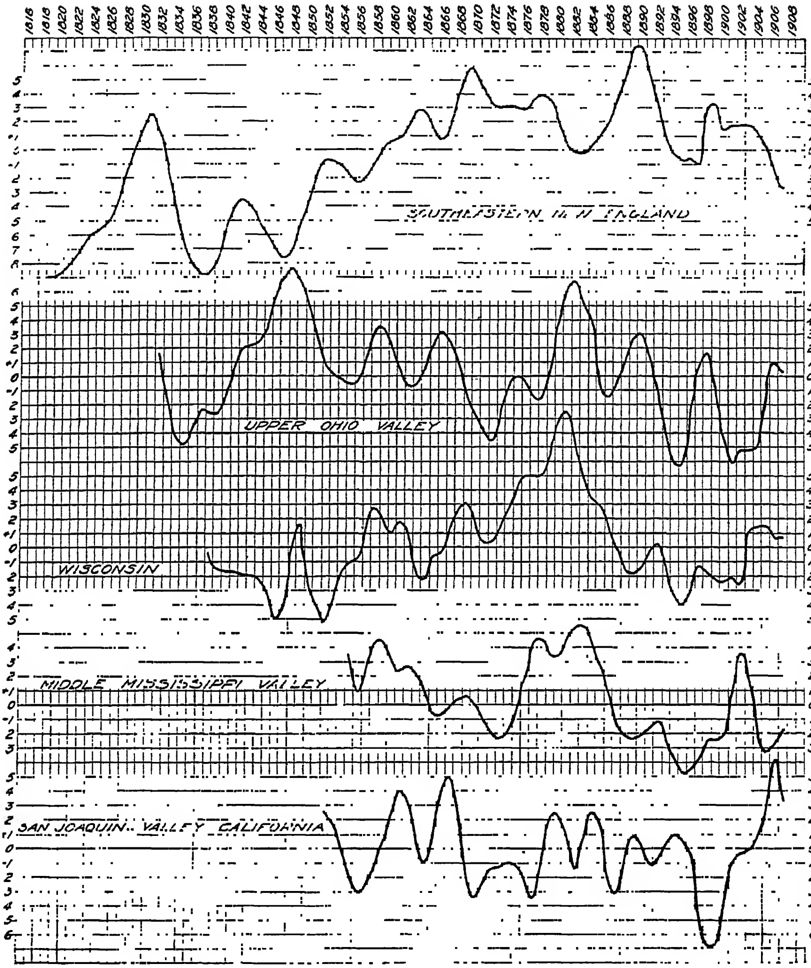


FIG. 117.—Rainfall, Progressive Means (see page 208).

in the progressive mean of over ten inches. In Wisconsin, from the year 1840 to 1881, an increase of 13.5 inches in the progressive mean is shown, while the years 1881 to 1902 show a decrease of 12 inches. It is evident therefore, that to demonstrate either an actual increase or decrease in the mean annual rainfall, records are required for a much longer period than is available in the United States or elsewhere.

The long periods during which the progressive mean is sometimes below or above the mean for the period should also be noted. For

example, in New England the progressive mean was below the mean for the period for twenty-six years from 1833 to 1859, and above for the twenty-three years from 1859 to 1882. In Wisconsin, the progressive mean was above the period mean for twenty years from 1867 to 1887, and below the mean for the ten years from 1892 to 1902. Usually, however, the departure in one direction is for more limited periods, as an examination of the various curves will show. The error that must therefore occur in drawing any conclusions from a short series of observations is manifest.

These diagrams of mean rainfall, together with much longer records in foreign countries, lead to the conclusion that while considerable variations must be expected, yet such variations are within certain limits, and that a record of forty years will give a mean from which the mean of any other similar period will hardly depart more than a few percent. While geological research shows conclusively that great changes in climatic conditions have taken place in times past, and undoubtedly will take place in the future, yet these changes have occupied thousands of years; and while the records of centuries may show radical variations in rainfall conditions, yet so far as the life of man is concerned, the variations in annual rainfall are due essentially to the great swing in the pendulum of conditions, the cause of which we know not, but which we can confidently expect when extremes are reached to gradually revert to the opposite conditions. In other words, it is clearly evident that so far as the life of man is concerned, the rainfall conditions remain essentially unchanged except for the variations from average conditions, the extent of which can be fairly well established by an examination of available records. In the changes of ages, the character of which we have not sufficient data to recognize, mankind has no practical interest.

107. Detail Study of Local Variation in Annual Precipitation.— Having briefly discussed the general variations in annual rainfall, a better idea of the subject may be secured by examining the rainfall of a smaller territory in greater detail, and for this purpose the State of Wisconsin has been selected. Fig. 118, page 213, shows both the actual departure from the mean for the recorded period of rainfall observations at various stations in or near Wisconsin, and the progressive mean during such period. It will be here noted that the variations in the annual rainfall, even in the limited area considered, are not synchronous. The period of maximum rainfall at Milwaukee was from 1874 to 1879, while at Madison it was from 1878 to 1886.

While in some cases a certain similarity exists in the progressive mean, in no two cases are the variations uniformly parallel. The records of precipitation show not only a considerable variation in the annual amount, but also show that the annual distribution throughout the

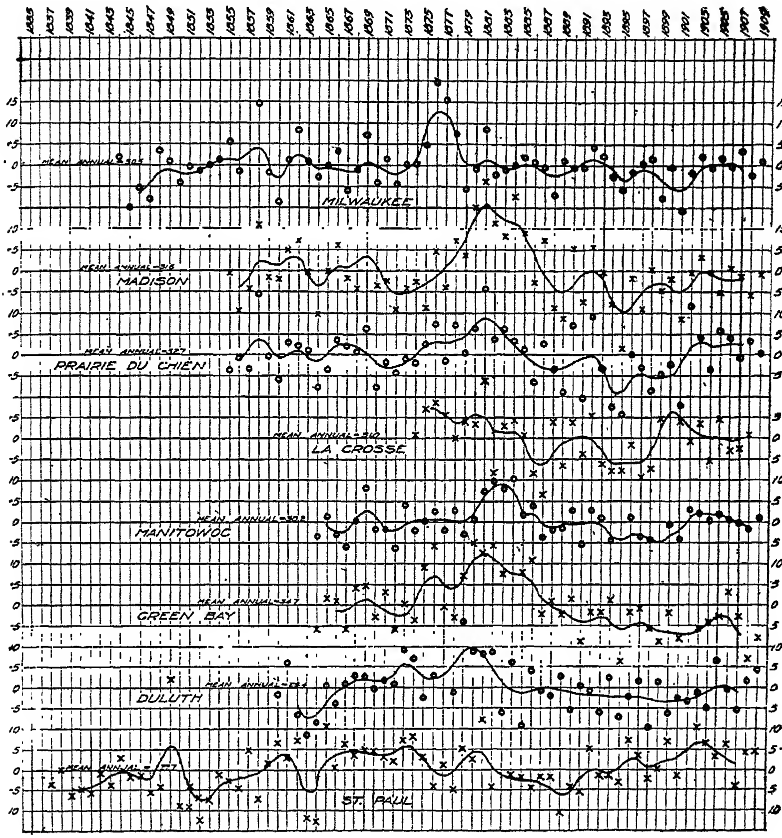


FIG. 118.—Annual Rainfall and Progressive Means for Wisconsin Stations (see page 208).

state is never the same. It is seen from these cuts that the rainfall does not only vary from year to year at any given locality, but the variations in adjoining localities are often in opposite directions. As the variations in runoff from any drainage area must be due to variation in the rainfall at all points on such area, the data from which the net results must be deduced are, from any extensive drainage area, consequently very complex.

The variation in the total quantity of the annual precipitation on any drainage area is frequently very great, although it is usually less so than at any particular station. At Madison (see Fig. 119) in the last twenty-five years, the extreme variations in the total annual rainfall have been from a minimum of thirteen inches to a maximum

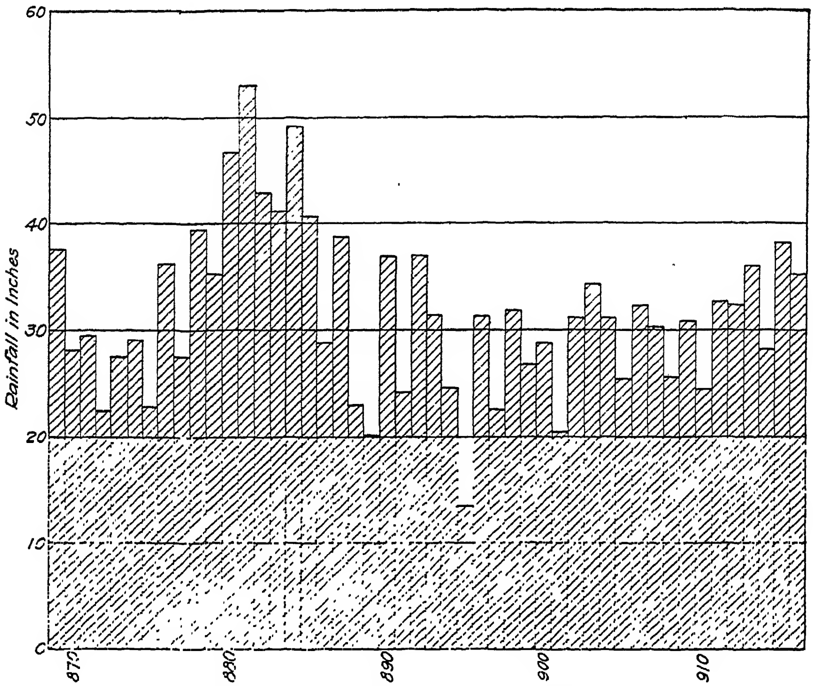


Fig. 119.—Variation in Annual Rainfall at Madison, Wis.

of fifty-two inches, the minimum being only twenty-five per cent of the maximum. Broadly speaking, such a variation is unusual, for, as a general rule, in the upper Mississippi Valley the minimum rainfall is usually about fifty per cent. of the maximum.

108. Cycles in Rainfall.—It has sometimes been pointed out when considering the variation in the total annual precipitation that these variations occur in a more or less definite cycle. Such cycles depend upon the regularity of the recurrence of factors producing precipitation. The great variations which sometimes occur in cycles of more or less regularity are apparently very dissimilar in different areas and are produced by great cosmic changes of which little is known. A general cyclic character can be roughly traced in some of the curves

shown in Fig. 117. In this figure the progressive mean for the three sections of the United States east of the Mississippi River, was calculated from the averages of the rainfall observations at several localities in the sections mentioned.[2] The cycle as far as it can be developed for the southern New England States is of ten-year periods; that for the upper Ohio Valley for eight-year periods; and that for Wisconsin for a twelve-year period. Such cycles, however, seem to be of too indefinite a character and have too great a local difference to be of any value in the prognostications of future conditions. This fact is especially true when the actual variations in the annual rainfall, as well as the progressive mean, are shown, as is the case in Fig. 118. As might be inferred from the maps shown in Figs. 112 and 113, there is no uniformity in either maximums or minimums prevailing within a limited locality, and the cycle is therefore of little practical utility in the consideration of engineering problems.

109. **Extreme Variations in Local Annual Rainfall.**—A knowledge of the variations to be expected in the annual rainfall of any locality, and the length of time required to make rainfall records a safe basis for future estimates, is of much interest in regard to many water supply problems. This subject was studied in great detail in a paper by Alexander A. Binnie,[3] and he shows graphically (Fig. 120, page 216) the average deviation from the mean annual rainfall for periods of observation extending from one year to thirty-five years as determined by his studies. It should be especially noted that the deviations shown are *average* deviations and that the maximum and minimum deviations at any single location are materially different. (See Table 15).

In the first part of this table the irregularities in the forty, forty-five and fifty year periods are due to the fact that the number of records from which these deviations were calculated was very small.

Binnie's paper contains a large amount of valuable information, and represents a large amount of labor in its compilation and treatment; it is unfortunately somewhat in error on account of the fact that the author divided his data into only single sets of periods instead of making all possible combinations. For example, in an eighty-year group, sixteen five-year consecutive periods were used for comparison where seventy-six groups were possible, and instead of eight ten-year groups, seventy-one were possible.

[2] Bulletin No. 425, University of Wisconsin, "The Flow of Streams, etc."

[3] Institute of Civil Engineers, Vol. 109, 1891, pages 89 to 172.

Ordinarily it would be found that among this greater number of combinations, greater discrepancies from the mean rainfall would be found than are shown by the author, as pointed out by Mr. Blanford, and in general Mr. Binnie's paper and diagram will therefore show somewhat less deviation of the average of short-time records from the real

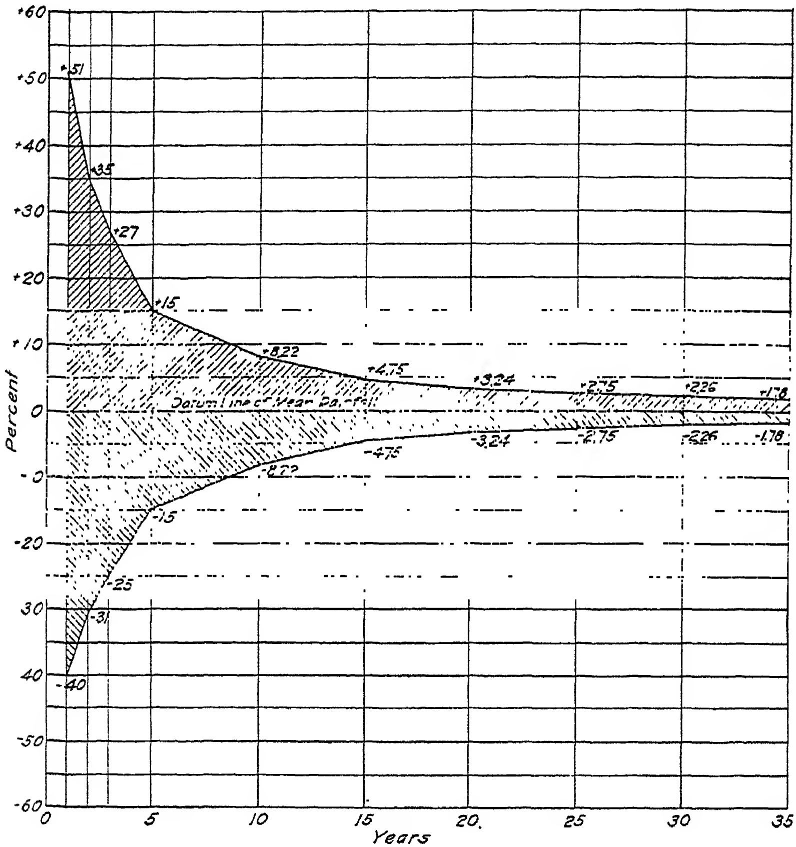


Fig. 120.—Average Deviation from Mean Annual Rainfall, by Binnie (see page 215).

mean annual rainfall than will probably be found in many extreme cases.

110. Expectancy of Future Rainfall Occurrences.—The future must be judged by the past, and the study of rainfall variations is generally for the purpose of judging what extremes must be expected in the future. The occasional occurrence of more extreme conditions

TABLE 15.

Deviations from the Mean Value of the Annual Rainfall During the Period of Record—Expressed in Percentages of the Mean Local Rainfall as Determined by A. R. Binnie.

From 42 Records of from 50 to 97 Years

	5	10	15	20	25	30	35	40	45	50
Max. Dev. above Mean..	32.1	19.3	11.9	11.6	9.9	9.2	7.1	5.7	4.8	3.8
Max. Dev. below Mean..	30.4	18.9	15.5	12.9	10.7	9.7	7.7	5.1	2.9	4.1
Ave. Dev. above Mean..	17.61	9.67	5.59	4.43	3.43	2.91	2.41	3.23	2.60	2.72
Ave. Dev. below Mean..	16.09	9.62	6.57	5.11	3.78	3.16	2.20	2.21	1.34	2.33
Min. Dev. above Mean..	6.8	1.0	1.1	0.0	0.0	0.0	0.0	0.3	0.7	1.5
Min. Dev. below Mean..	7.8	4.7	0.8	0.0	0.0	0.0	0.0	0.0	0.1	0.0
Average Deviation	16.85	9.64	6.08	4.77	3.60	3.02	2.30	2.77	1.96	2.52
Extreme Dev. from Ave.	16.15	9.66	9.42	8.13	7.10	6.67	5.40	3.28	2.83	1.58

From 26 Records of from 50 to 60 Years

	5	10	15	20	25	30	35
Max. Dev. above Mean.....	23.2	14.9	9.2	5.1	7.3	5.2	4.5
Max. Dev. below Mean.....	29.6	16.1	12.5	9.2	9.0	6.9	4.7
Ave. Dev. above Mean......	15.35	8.08	3.87	2.47	2.50	2.17	1.73
Ave. Dev. below Mean......	14.51	8.37	5.64	4.08	2.94	2.37	1.86
Min. Dev. above Mean......	6.8	1.0	0.0	0.0	0.0	0.0	0.0
Min. Dev. below Mean......	7.8	4.7	0.8	0.0	0.0	0.0	0.0
Average Deviation	14.93	8.22	4.75	3.24	2.77	2.26	1.78
Extreme Dev. from Ave.....	14.67	7.88	7.75	5.95	6.25	4.64	2.72

than have hitherto been experienced is a warning that as time passes even still greater variations must be expected.

A graphical analysis of the annual rainfall at Madison, Wisconsin (Table 20, p. 238), is shown in Fig. 121. In this figure the two limiting horizontal lines show the extreme maximum and minimum annual rainfalls in the 48 years of record, namely 52.93 and 13.49 inches. The next highest and lowest annual rainfalls, namely 49.19 and 20.17 inches, are platted on the 24-year ordinate point as representing the next in magnitude of the two highest or lowest occurrences in 48 years, and therefore, the limit above and below which two annual rainfalls must be expected within 24 years. In the same manner the least and greatest of the three highest and lowest rainfalls that have occurred in the 48 years of experience are platted on the 16-year ordinate, and so on throughout the table, the points platted furnishing a guide for the establishment of the lines marked "lower limit of maximum experience," and "upper limit of minimum experience." The shaded area between these lines and

the horizontal lines first mentioned shows the limiting field of the experience in Madison.

The "mean curve of maximum experience" and the "mean curve of minimum experience" are the curves drawn through the means of the one, two, three, four, etc., highest and lowest records respectively, in accordance with the data shown in Table 16.

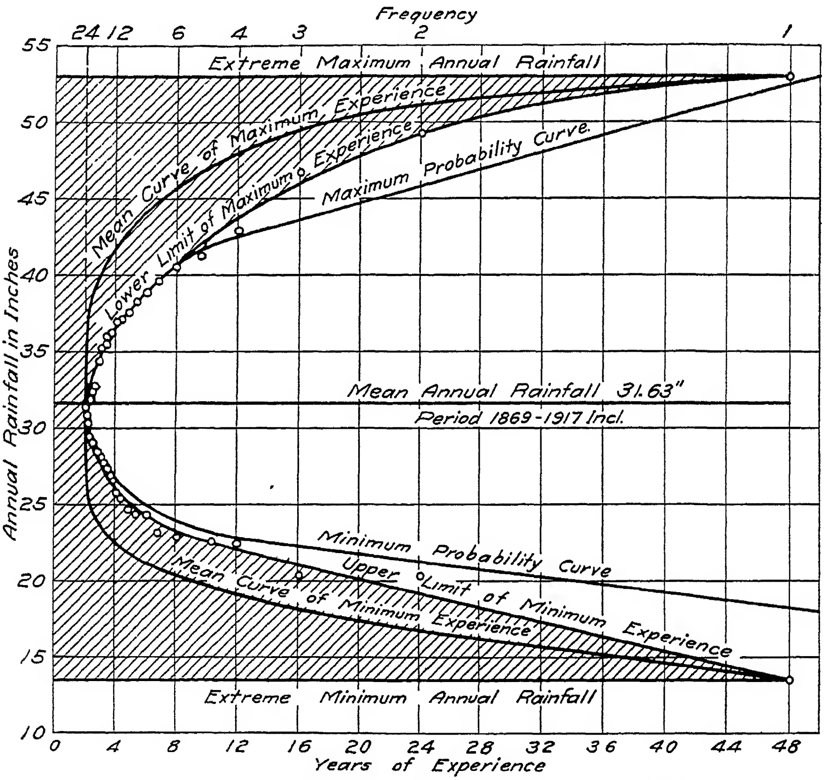


FIG. 121.—Graphical Analysis of Rainfall Experience at Madison, Wis.

The limiting curves above noted are platted from Columns 2 and 3 of this Table, and the mean curves are platted from Columns 5 and 6. This diagram shows that based on past experience a maximum rainfall of 52.93 inches should be expected in 48 years; that in 24 years two maximum rainfalls must be expected of 49.19 inches or more, averaging 51.06 inches, etc.

The prolongation of this curve which is expanding from the average in both directions, would indicate that as time passes greater and lesser annual rainfalls must be expected and an estimate of such intensity may

be made by prolonging the curve. Such a use of the data is, however, extremely dangerous as it is evident that with any gradual increase, if the time is sufficiently prolonged, a minimum of zero would be reached on one hand and an infinite rainfall on the other, both of which are absurd. Judgment would indicate that such curves must ultimately become parallel with the base when the most extreme conditions are reached, but what those extreme conditions are, is indeterminate.

TABLE 16.

Experience Table of Annual Rainfalls at Madison, Wis.

Order of Magnitude	Rainfalls in Order of Magnitude Inches		Number of Annual Rainfalls Averaged	Mean Annual Rainfall Inches	
	Maximum	Minimum		Maximum	Minimum
1	52.93	13.47	1	52.93	13.49
2	49.19	20.17	2	51.06	16.83
3	46.72	20.24	3	49.61	17.97
4	42.89	22.44	4	47.93	19.90
6	40.58	22.80	6	45.57	20.29
8	38.89	24.24	8	43.98	21.13
12	36.98	25.67	12	41.81	22.43
16	35.21	28.13	16	40.28	23.70
24	31.25	31.25	24	37.60	25.66

Mean Annual Rainfall, 31.63.

Fig. 121 also contains a maximum and minimum probability curve which is discussed in Section 111.

Such curves, while instructive, can not safely be used for estimating future occurrences except within wide limits. This is well shown by comparing the three experience curves of the annual rainfall at Boston, Massachusetts, shown in Fig. 122, p. 220. In this case, 100 years of observation are available and curves have been drawn for the 50 years from 1818 to 1867 and from 1868 to 1917, both inclusive, as well as for the entire 100 year period.

From Fig. 122 it will be seen that during the first 50 years both the maximum and the minimum rainfalls for the entire 100 years were experienced, and the occurrence of that period could not be inferred from the experience curve for the last 50-year period. The curve for the last 50 years if taken by itself would indicate that the minimum rainfall had been reached in that period, but the curve of the first 50 years shows that such was not the case and that even a lower rainfall must be expected.

111. **Rainfall Data and the Law of Probabilities.**—Rainfall and other meteorological and hydrological data can be studied to advantage on the basis of the Laws of Probabilities. The method has been

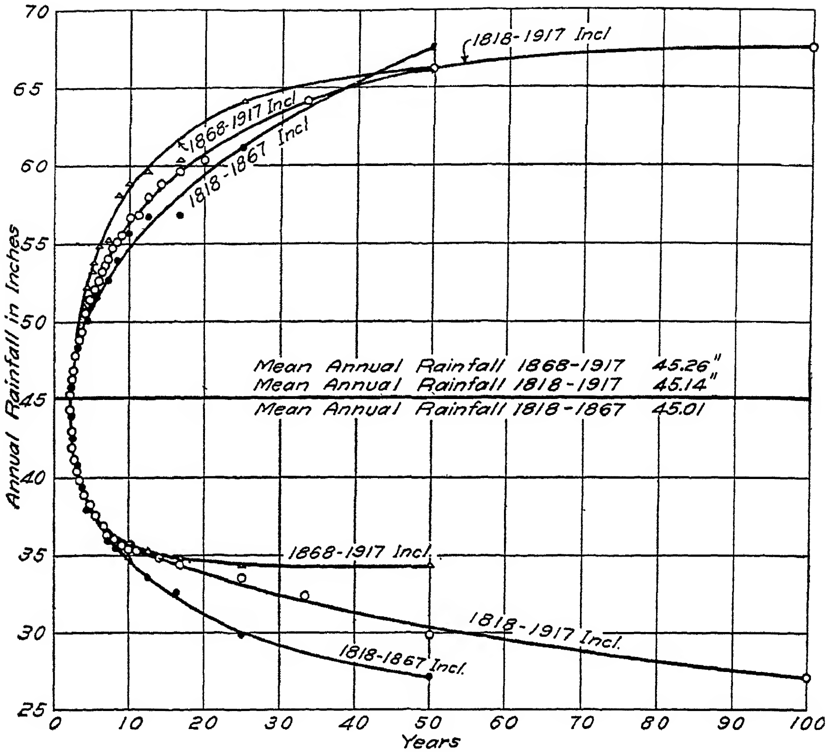


FIG. 122.—Graphical Analysis of Rainfall Experience at Boston, Mass.

utilized in certain extended investigations by Mr. Allen Hazen, Mr. Thorndike Saville and others, and the methods are described in some detail in the references given. From Saville's paper, or from any work on Least Squares, it appears that if

Z = most probable value of a term in a series of observations or the mean of such observation.
n = number of observations.
M = any observation.
v = variation of a single observation from the mean.
r = probable variation of a single observation.
R = probable variation of the mean.
Σ = summation; then

$$Z = \frac{\Sigma M}{n} = \text{mean}$$

$r = 0.6745,$ $\quad$ - = probable variation of any single observation

$$R=\frac{r}{\sqrt{n}}=0.6745\sqrt{\frac{\Sigma v^2}{n(n-1)}}=\text{probable variation of the mean}$$

$$\sqrt{\frac{\Sigma v^2}{n-1}}=\text{standard variation}$$

$$\frac{\sqrt{\frac{\Sigma v^2}{n-1}}}{\Sigma M}=\text{coefficient of variation.}$$

In Table 17 the annual rainfalls of Madison for 48 years of record are shown in the order of their magnitude. The difference (v) and

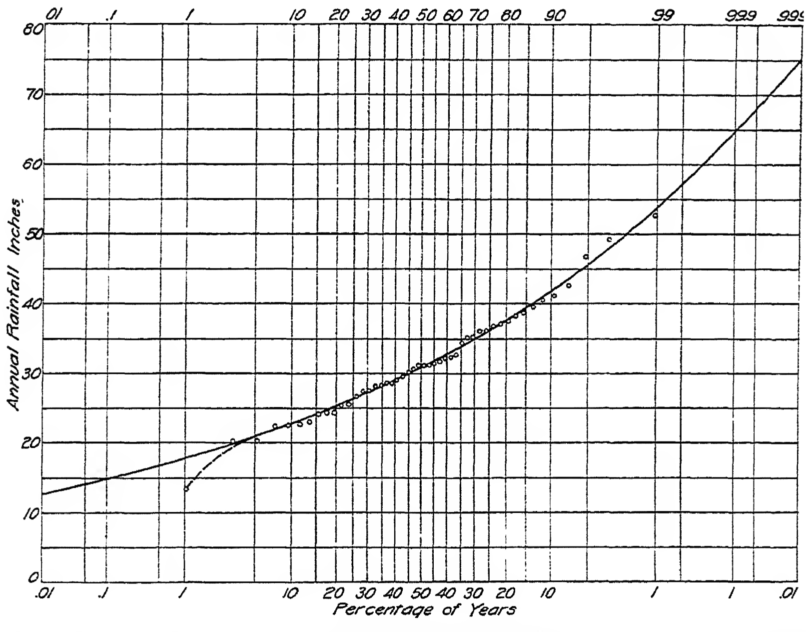


Fig. 123.—Probabilities of Annual Rainfall at Maidson, Wis. (Probability scale) (see page 197).

the square of the difference (v^2) and the percentage of the time which the equivalent rainfall is below the amount given in the first column, are also given. From this table a probability curve is platted on the Hazen probability paper (Fig. 123).

Each point in the order of its magnitude is platted in the center of a strip of width (in per cent.) proportional to the ratio of 100% to the full number of terms used, i. e.; in this case each strip will occupy $\frac{100}{48}$

or 2.08%, and the first and last terms will be at absissa 1.04%, the distance between points being 2.08% in each case. (Fig. 123.)

If the data corresponds essentially with the normal law of error, the platted points will lie approximately in a straight line. In this case the points fall on a curve which departs somewhat from the straight normal line of errors and is indicated by the curve which very closely approximates the rainfall observation at Madison. From these lines the frequency of the occurrence of any given amount of annual rainfall at Madison can be determined from the principle that the frequency or number of years during which a given rainfall will occur once is equal to the ratio of unity to the percentage of time in which such occurrence has taken place. The relations for Madison, as determined from this curve, are shown in Table 18.

TABLE 17.

Yearly Rainfall inches in order of magnitude	Variations from the mean	Variations Squared	Per cent. of total Time Cumulative Total
13.49	18.14	329.07	1.04
20.17	11.47	131.56	3.12
20.24	11.39	129.73	5.21
22.44	9.19	84.46	7.29
22.58	9.05	81.90	9.37
22.80	8.83	77.96	11.46
23.06	8.57	73.45	13.54
24.24	7.39	54.61	15.62
24.37	7.26	52.71	17.71
24.59	7.04	49.56	19.79
25.49	6.14	37.70	21.87
25.67	5.96	35.52	23.96
26.81	4.82	23.23	26.04
27.49	4.14	17.14	28.12
27.67	3.96	15.68	30.21
28.13	3.50	12.25	32.29
28.17	3.46	11.97	34.37
28.78	2.85	8.12	36.46
28.78	2.85	8.12	38.54
29.05	2.58	6.66	40.62
29.45	2.18	4.75	42.71
30.29	1.34	1.80	44.79
30.83	0.80	0.64	46.87
31.25	0.38	0.14	48.96
31.25	0.38	0.14	51.04

TABLE 17—*Continued.*

	Yearly Rainfall inches in order of magnitude	Variations from the mean	Variations Squared	Per cent. of total Time Cumulative Total
	31.35	0.28	0.08	53.12
	31.46	0.17	0.03	55.21
	31.91	0.28	0.08	57.29
	32.32	0.69	0.48	59.37
	32.38	0.75	0.56	61.46
	32.72	1.09	1.19	63.54
	34.40	2.77	7.67	65.62
	35.21	3.58	12.82	67.71
	35.33	3.70	13.69	69.79
	36.04	4.41	19.45	71.87
	36.15	4.52	20.43	73.96
	36.98	5.35	28.62	76.04
	37.10	5.47	29.92	78.12
	37.53	5.90	34.81	80.21
	38.23	6.60	43.56	82.29
	38.89	7.26	52.71	84.37
	39.54	7.91	62.56	86.46
	40.58	8.95	80.10	88.54
	41.13	9.50	90.25	90.62
	42.89	11.26	126.79	92.71
	46.72	15.09	227.70	94.79
	49.19	17.56	308.36	96.87
	52.93	21.30	453.70	98.96
Total	1,518.07		2,864.43	
Mean	31.63			
Median	31.25			

$$\text{Most probable value of annual rainfall} = \frac{1518.07}{48} = 31.63''.$$

$$\text{Standard variation} = \sqrt{\frac{2864.43}{(48-1)}} = 7.807.$$

$$\text{Coef. of variation} = \frac{7.807}{31.63} = 0.2468.$$

$$\text{Probable error of a single observation} = 0.6745. \quad 7.807 = 5.266.$$

$$\text{Probable error of the mean} = \frac{5.266}{\sqrt{48}} = 0.760.$$

$$\text{Per cent. of total time represented by each observation} = \frac{100}{48} = 2.0833.$$

TABLE 18.

Probabilities of Rainfall at Madison, Wisconsin.

Amount of Rainfall in inches	Relative Time of Occurrence	Equivalent Time in year	Frequency Once in
26— or 36+	25	11.8	4 years
24— or 40+	15	7.2	6.7
23— or 42+	10	4.8	10.
21— or 46+	5	2.4	20.
18— or 52+	2	0.96	50.
17.5— or 53.5+	1	0.48	100.

To determine the limiting rainfalls for a given period the corresponding ordinates of the percentage of years is found from the equation

$$\text{Percentage of years} = \frac{100}{\text{length of period}}$$

Thus, for a five-year period the percentage of years is $\frac{100}{5} = 20$ and the ordinates to the curve at the percentage 20 are 37.5 and 25, and these figures mean that in a five-year period we should expect on an average one rainfall of 37.5 inches or more and one annual rainfall of 25 inches or less.

It should be noted that the conclusions shown in Table 18 and platted in Fig. 121, which are based on the data of Table 17 and Fig. 123, when near the mean are well established and may be considered as fairly safe and conservative, and that as the departures from the mean increase the data become more limited and the conclusions are subject to greater error. Even the frequency of once in 20 years for rainfalls of 21 inches or less and 46 inches or more will likely be found in error where the data for 100 years or more are available for study, and the frequency for one rainfall of 18 inches or less and of 53 inches or more once in 100 years is entirely unwarranted because the period is beyond experience. Such an estimate is the best that can be made with the data at hand, but should not be taken as a dependable prediction.

It should be noted, however, that this method of investigation shows the extraordinary character of the minimum rainfall record and also indicates the fact that the three highest rainfalls are somewhat inconsistent with the balance of the record. It should also be noted that a calculation of the probable extreme rainfall of once in 100 years by this method is more conservative than if based on the extension of the limiting curves of the actual experience platted in Fig. 122. This results from the eliminating of inconsistencies by this latter method.

If we calculate the frequency of the minimum rainfall of 13.39 inches from the curve in Fig. 123, the frequency indicated would be once in 4,000 years. This must be regarded as an absurd deduction for this rainfall had already occurred in 48 years' record and it is possible that other years in the next 100 may fall short of this amount, although such an event seems improbable from the data available. This method cannot safely be used to project estimates far into the future beyond the limits of experience.

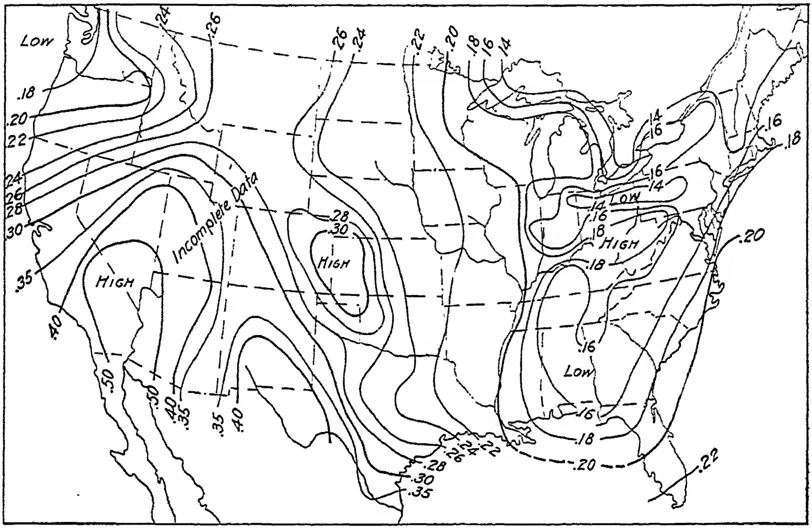


FIG. 124.—Hazen's Map of Rainfall Coefficients.

112. **Application of Probability Calculations.**—Mr. Allen Hazen prepared a map of the United States [4] (Fig. 124) on which he has shown the relative variation in the quantity of annual rainfall in various parts of the country by means of the coefficient of variation as expressed above. Mr. Hazen says:

"For the eastern part of the United States the records used are sufficient to show the normal conditions with a fair degree of accuracy. In the west the relative variations are greater, the records are shorter and the stations often farther apart and the results thus less reliable.

"The map is to be regarded as a first rough approximation. It serves to give a fairly accurate idea of the general conditions of variation in annual rainfall in the United States, but in detail it must be

[4] Engineering News, Jan. 6, 1916—Allen Hazen.

expected that more ample data, or even more complete use of existing data by extending the studies to cover everything available, would result in changes in the positions of the lines. Such changes are most likely near mountains and in about that third of the country nearest the Pacific Coast.

"The coefficient of variation is lowest on the Atlantic Coast. That means that one can count on getting more nearly the normal rainfall each year; and on the Atlantic Coast the coefficient does not range through wide limits. If one's experience were limited to this part of the country, he might almost neglect the range and assume that there was everywhere the same chance of a very dry year, such, for example, as is represented by a rainfall of only sixty per cent of the normal. This is in general the conclusions reached by Binnie for the data studied by him. It does not hold, however, for the whole United States. As one goes west, the coefficient of variation in annual rainfall increases; that is to say, the chance of a very dry or a very wet year (relatively) is increased.

"In New York the coefficient of variation is 0.15; at San Francisco it is 0.30. This means that on an average the relative variations in annual rainfall at San Francisco are twice as great as at New York. A year forty per cent short of the normal rainfall comes as often at San Francisco as one twenty per cent short of the normal comes in New York.

"By following this method of investigation it will not be hard to find quite definitely just how often, on an average, a year of any assumed relative wetness or dryness will come, and also to find what the chances are of years of any degree of dryness coming within a given period.

"Other things being equal, the variations to be expected in any period at different localities will always be in direct proportion to the coefficients of variations in the respective places."

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CHAPTER X

SEASONAL RAINFALL IN THE UNITED STATES AND ITS VARIATION

113. **Seasonal Variation in Rainfall.**—Climatic conditions are, in a general way, fairly consistent, and as the seasons change, conditions obtain favorable or unfavorable for precipitation. The maximum and minimum monthly rainfall occurs, therefore, at every locality at fairly

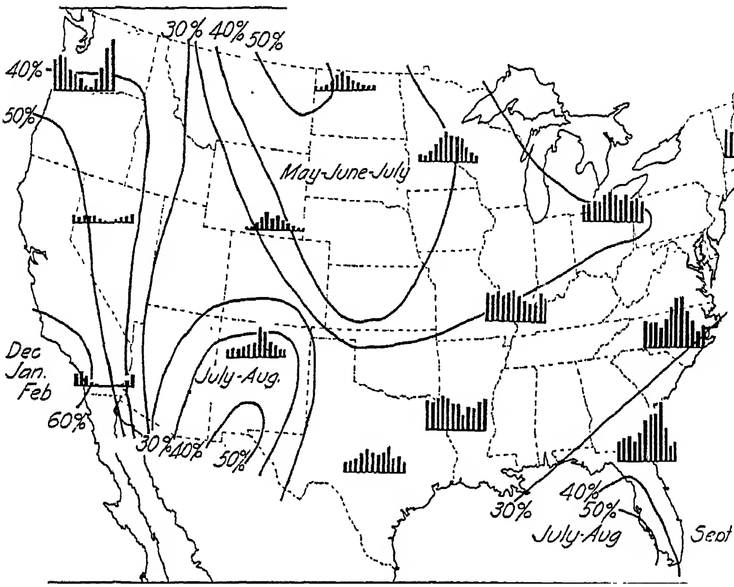

Fig. 125.—Seasonal Rainfall of the United States.

definite periods. Rainfalls vary considerably from year to year, but have, nevertheless, the same general character. The mean seasonal distribution of rainfall in the United States and the percentage of the annual precipitation that commonly falls during the wet season of the year, are shown in Fig. 125, upon which the radically different occurrence of rainfall in various localities is indicated.

Fig. 126 shows the percentage of the mean annual rainfall that commonly occurs from April 1 to September 30. It may be noted that the high percentage of the rather low rainfall on the Great Plains occurring during the growing season is a condition favorable for agriculture.

Fig. 127, page 230, shows typical fluctuations of the rainfall for various months in the year at a number of places throughout the United States; and more extended types of the monthly distribution of precipitation in the United States are shown in Fig. 128, page 231.

In Fig. 128 the monthly averages of a number of stations have been reduced to percentages of the average annual fall. The character of the monthly distribution varies widely at different locations, but will be seen

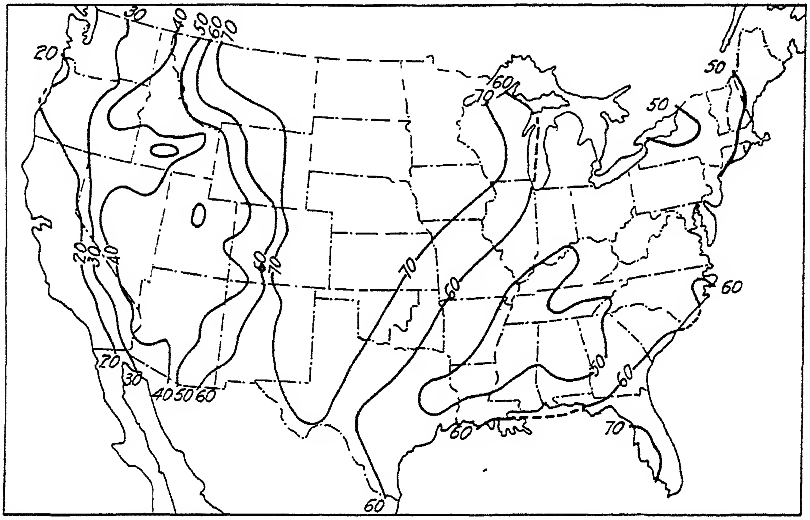

FIG. 126.—Percentage of Mean Annual Rainfall Occurring from April 1 to September 30 (see page 228).*

to have a similar character wherever similar conditions prevail. Thus the New England States present a similarity in the distribution of the monthly rainfall. A similarity in the monthly distribution is also found throughout the lake region and the Ohio Valley. The monthly distribution throughout the Great Plains is also similar, and a marked similarity exists at points along the Pacific Coast, although the actual amounts of precipitation may and do vary quite widely over these same areas.

An examination of the diagram will at once show the wide variation in the distribution of rainfall through the growing or crop season in the various districts.

Irrigation in Italy, South Africa and several other countries, is made necessary because the amount of rainfall during the growing season is deficient, although the annual precipitation may be and fre-

*Monthly Weather Review, July, 1917.

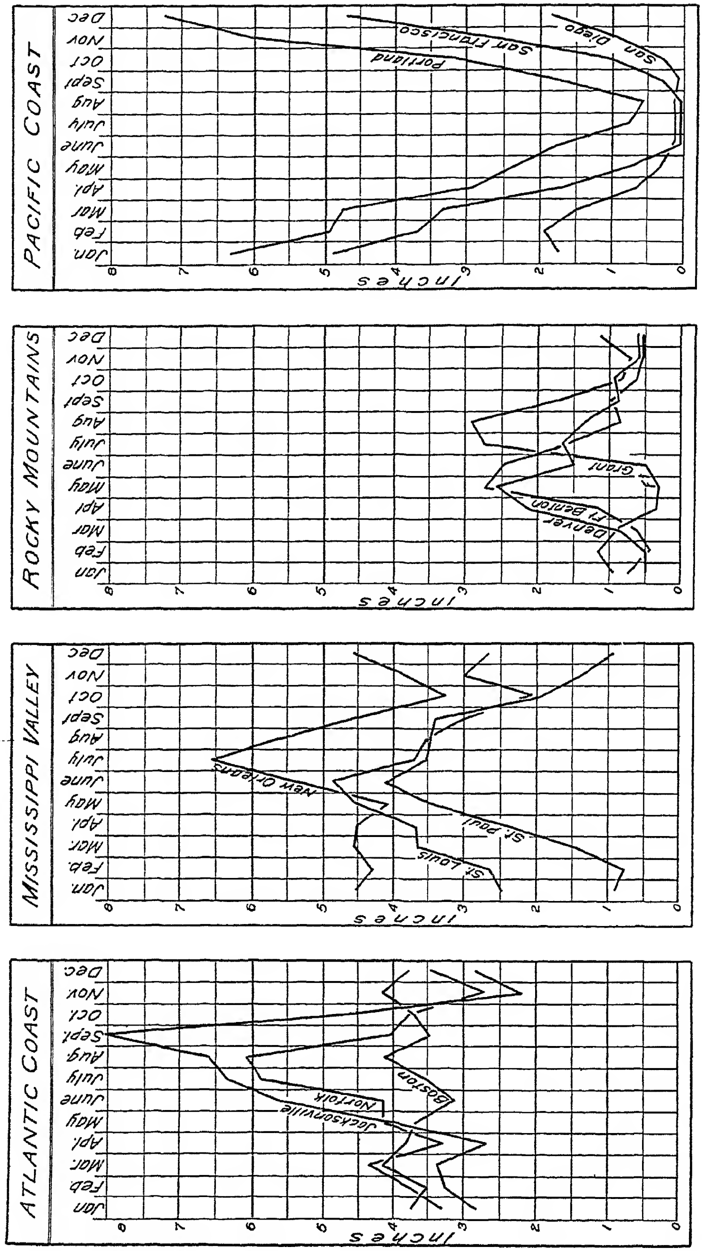

FIG. 127.—Typical Fluctuations of Rainfall (see page 229).

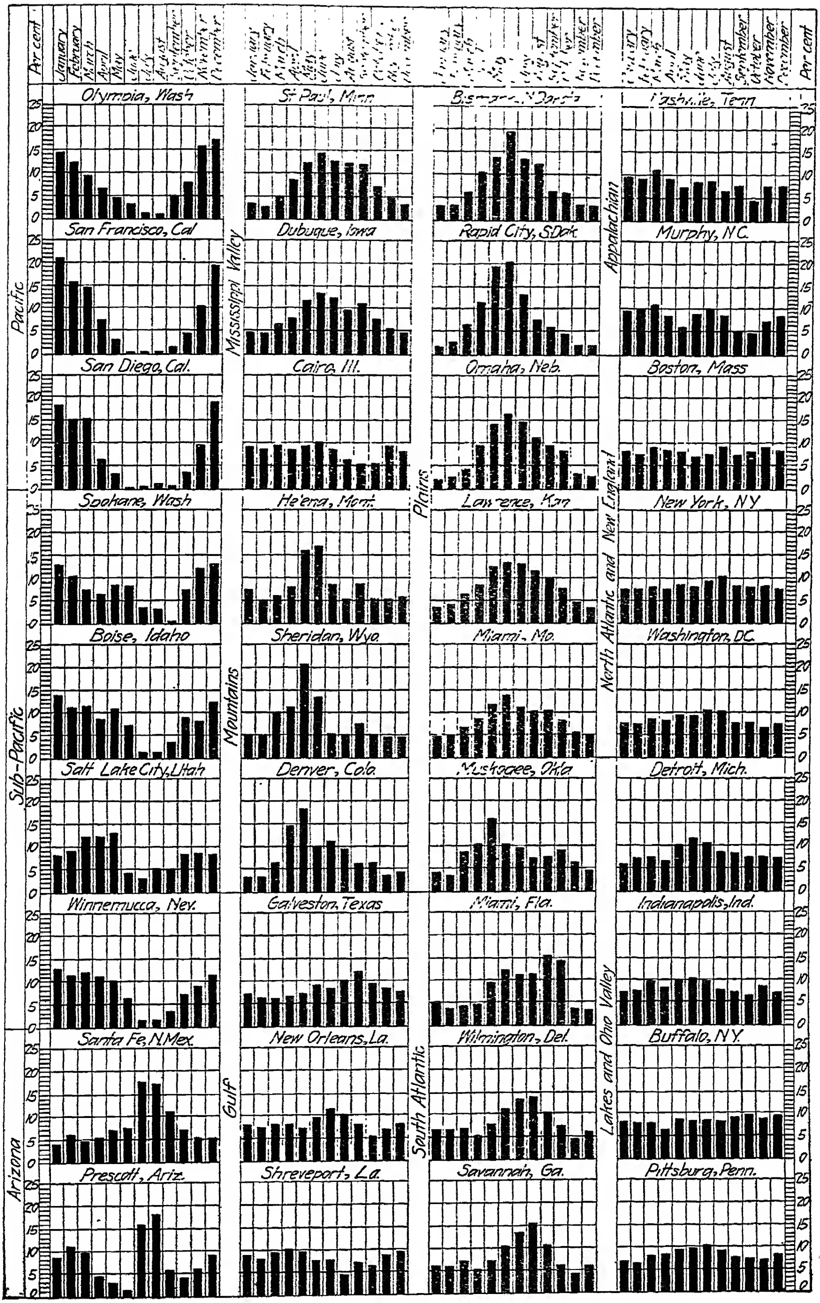

FIG. 128.—Monthly Rainfall in Per cent. of the Annual (see page 229).

quently is as much or more than occurs in places which enjoy a quantity of rainfall adequately ample to support agriculture. Milan, the center of the irrigated district, has an average annual rainfall of slightly more than forty inches.

This condition of insufficient rainfall during the summer months is occasioned principally by the effect of the prevailing winds, coupled with the seasonal land temperatures.

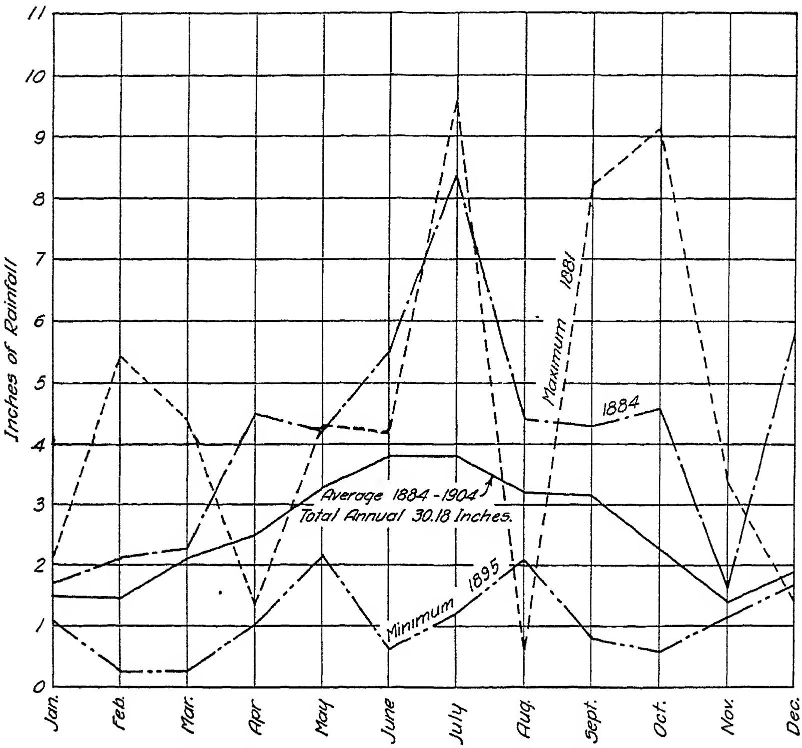

Fig. 129.—Fluctuations of Monthly Rainfall at Madison, Wis.

The North Pacific Coast, which receives the major portion of its annual precipitation during the winter, undergoes this condition because of the greater cooling effect of the land at this season upon the westerly ocean breezes.

114. **Local Variations in Seasonal Distribution of Rainfall.**—The total amount of the monthly rainfall is subject to much wider variation than that of the annual rainfall as might normally be expected from the nature of the occurrence of precipitation. These monthly amounts differ very largely from year to year and are subject to such wide

TABLE 19.

Precipitation at Madison, Wisconsin.

Year	Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total
1869	2.09	2.35	0.79	3.08	4.90	6.14	3.63	5.92	2.68	2.66	2.05	2.64	37.53
1870	3.35	1.35	3 85	0.18	1.09	1.92	5.25	3.85	4.00	2.09	0.53	0.67	28.13
1871	2.32	1.43	2.96	2.00	3.31	4.93	2.11	3.35	0.47	3.07	1.35	1.15	29.45
1872	1.20	0.40	2.18	1.82	2.83	2 44	1.26	2.24	5.11	0.60	0.76	1.60	22.44
1873	1 40	0.60	2.07	1.26	3.53	6.60	0.82	2.76	2.54	1.96	2.15	1.80	27.49
1874	3.64	0.95	0.95	1.26	2.14	2.85	5.00	1.40	5.46	1.44	3.51	0.45	29.05
1875	1.10	2.80	0.90	1.87	2.61	3.37	0.97	2.56	2.08	1.96	0.40	2.18	22.80
1876	2.31	1.60	2.27	2.65	5.18	4.57	4.25	3.42	3.41	1.59	2.31	2.59	36.15
1877	1.00	0.30	3.40	T	1.02	4.77	3.84	3.76	0.64	4.12	2.81	2.01	27.67
1878	0.40	1.19	2.45	2.87	4.64	4.20	7.56	4.28	6.54	3.78	0.76	0.79	39 54
1879	0.79	2.54	1.34	3.33	3.91	2.80	5.91	0.99	2.79	2.50	6.02	2.29	35.21
1880	2.75	1.75	2.11	5.48	4.45	9.31	6.00	5.90	4.44	1.68	1.68	1.17	46.72
1881	2.05	5.42	4.34	1.50	4.25	4.15	9.47	0.56	8.17	9.12	2.56	1.32	52.91
1882	1.33	1.74	4.73	4.21	2.89	7.76	2.70	6.83	1 91	4.14	2.62	2.03	42.89
1883	1.01	1.64	0.32	1.29	6.98	7.57	8.89	2.74	2.39	3.79	2.56	1.95	41.13
1884	1.68	2.12	2.31	4.51	4.21	5.47	8.44	4.39	4.25	4.60	1.53	5.68	49.19
1885	2.44	0.82	0.62	3.45	1.68	5.11	7.30	6.41	4.05	2.37	2.74	3.59	40.58
1886	3.33	2.35	4.67	2.48	2.02	1.08	0.79	5.05	2.29	2.21	1.21	1.30	28.78
1887	3.09	4.34	2.14	0.96	2.12	1.48	5.49	3.75	6.67	3.18	1.16	4.53	38.89
1888	1.74	1.01	2.61	1.85	3.76	2.95	2.26	1.27	1.04	1.68	1.32	1.57	23.06
1889	1.59	1.84	1.48	1.71	3.28	2.00	2.12	0.72	1.93	T	1.17	2.33	20.17
1890	1.81	2.01	2.38	2.22	5.03	7.72	1.81	4.23	2.62	4.59	1.94	0.62	36.98
1891	1 19	1.38	3.62	1.45	1.48	3.69	2.66	1.41	0.38	1.49	3.31	2.24	24.24
1892	2.42	1.94	1.38	3.94	6.98	7.61	2.32	3.43	3.·9	0.36	1.24	2.19	37.10
1893	1.06	1.05	2.29	4.53	2.28	6.69	4.64	1.42	2.67	1.85	1.30	1.68	31.46
1894	0.96	0.46	1.73	8.57	3.36	3.94	1.75	0.54	4.21	1.77	1.65	0.67	24.59
1895	1.12	0.26	0.27	1.06	2.58	0.59	1.21	2.08	0.91	0.58	1 03	1.80	13.49
1896	0.88	0.32	0.79	4.91	6.31	2.69	3.62	2.43	4.29	3.03	1.40	0.68	31.35
1897	2.22	0.92	2.38	2.51	0.51	4.03	1.79	2.73	1.73	0.86	1 35	1.67	22.58
1898	3.59	2.42	2.67	2.46	4.71	4.40	2.83	2.56	2.43	3.08	0 55	0.21	31.91
1899	0.16	0.42	1.94	2.69	4 92	2.64	3.22	3.57	3.35	1.58	0.96	1.37	26.81
1900	0.69	1.26	1.32	1.31	1.86	3.20	6.91	2.72	2.89	4.44	1.72	0.47	28.78
1901	0.62	0.59	2.77	0.45	2.41	2.40	1.54	1.33	4.16	2.49	0.46	1.02	20.24
1902	0.17	1.46	0.60	1.17	5.16	4.27	8.98	0.78	4.18	1.23	1.41	1.84	31.25
1903	0.11	1.11	3.50	2.88	4.38	1.39	6.70	6.95	3.54	2.18	1 07	0 60	34.40
1904	0.30	1.87	2.44	1.39	5.03	2.85	3.27	3.20	5.93	1.60	0.03	3.34	31.25
1905	0.77	1.28	1.74	1 43	6.40	2.88	2.27	2.48	0.58	2.25	2.23	1.17	25.49
1906	2.80	0.97	2.13	0.90	3.35	4.55	1.80	7.56	2.04	2.69	2.36	1.23	32.38
1907	1.89	0.28	1.80	3.00	2.69	2.80	5.84	3.59	4.69	1.14	1.22	1.35	30.29
1908	0.97	1.79	1.62	4.41	5.38	1.80	2 85	2.53	0 78	0.64	2.14	0.76	25.67
1909	2.33	1.70	1.12	7.19	2.49	0.29	2 78	4.39	2.20	0.91	2.28	3.15	30.83
1910	2 82	0.74	0.14	4.56	2.82	1.31	0.81	6.56	1.83	0.63	1.59	0.56	24.37
1911	0.60	3.40	0.47	2.44	2.63	3.64	1.68	3.78	5.85	2.92	3.56	1.75	32.72
1912	0.58	1.50	1.92	1.48	6.57	1.13	5.63	3.16	5.62	2.49	0.89	1.35	32.32
1913	1.64	1.12	2.41	1.54	6.63	3.73	8.47	1.59	4.32	2.53	1. 3	0.33	36.04
1914	0.70	0.92	1.15	1.84	5.97	3.46	1.49	3.60	3.49	3.09	0.70	1.76	28.17
1915	2 05	2.30	0.87	0.92	5.98	1.75	5.04	4.39	10.69	0.48	3.12	0.64	38.24
1916	3.07	0.39	2.93	3.51	2.38	4.52	2.66	4.24	5.73	2.97	1.69	1.24	35.33
Mean for 48 yrs.	1.64	1.51	2.02	2.45	3.77	3.80	3.93	3.32	3.48	2.34	1.75	1.65	31.63

variations as to sometimes render the character of this occurrence somewhat obscure, unless a number of seasons are considered, yet the same general character ordinarily prevails.

Figure 129, shows the extreme and the average variation of the monthly rainfall at Madison. The monthly rainfall in the various months differs widely in amount and is by no means proportional to the total annual rainfall for the year. It is especially observable that during the year of maximum rainfall, viz: for 1881, the rainfall

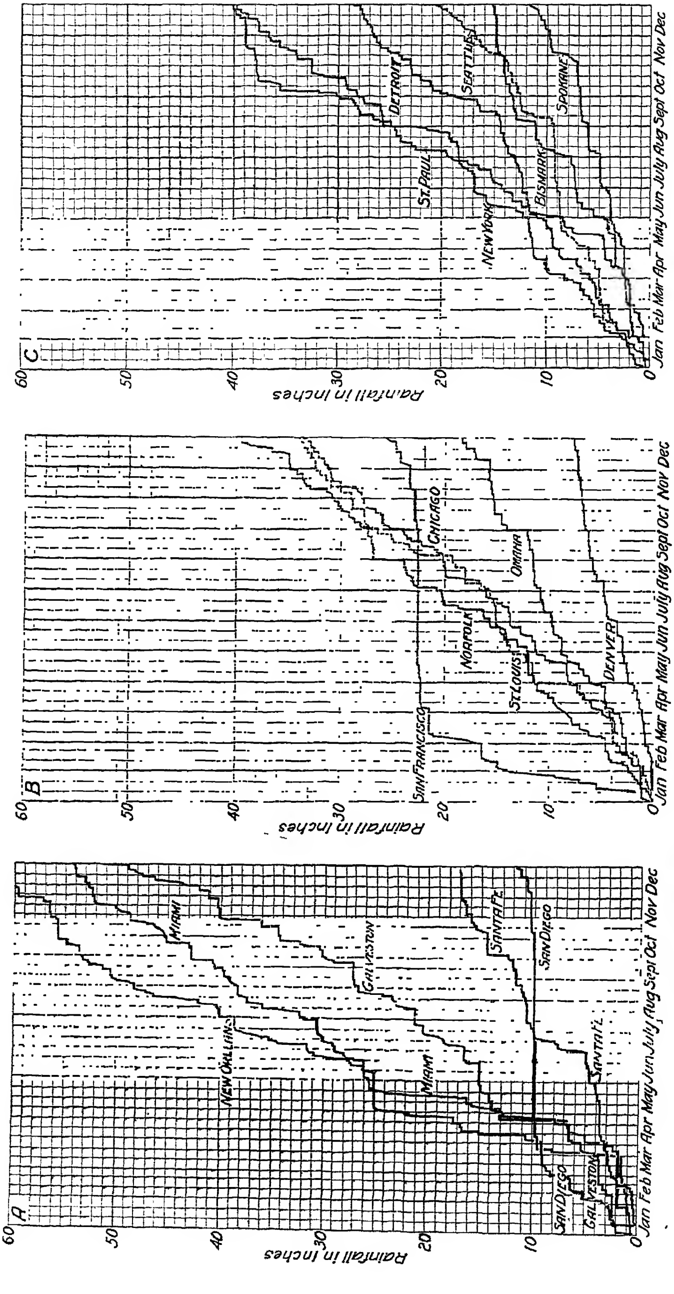

Fig. 130.—Mass Diagrams of Rainfall at Various Stations for 1911

for April was almost as low as for April of the year 1895 when the total annual rainfall was at a minimum. It is also observable that the rainfall for August, 1881, was less than the rainfall for August of 1895.

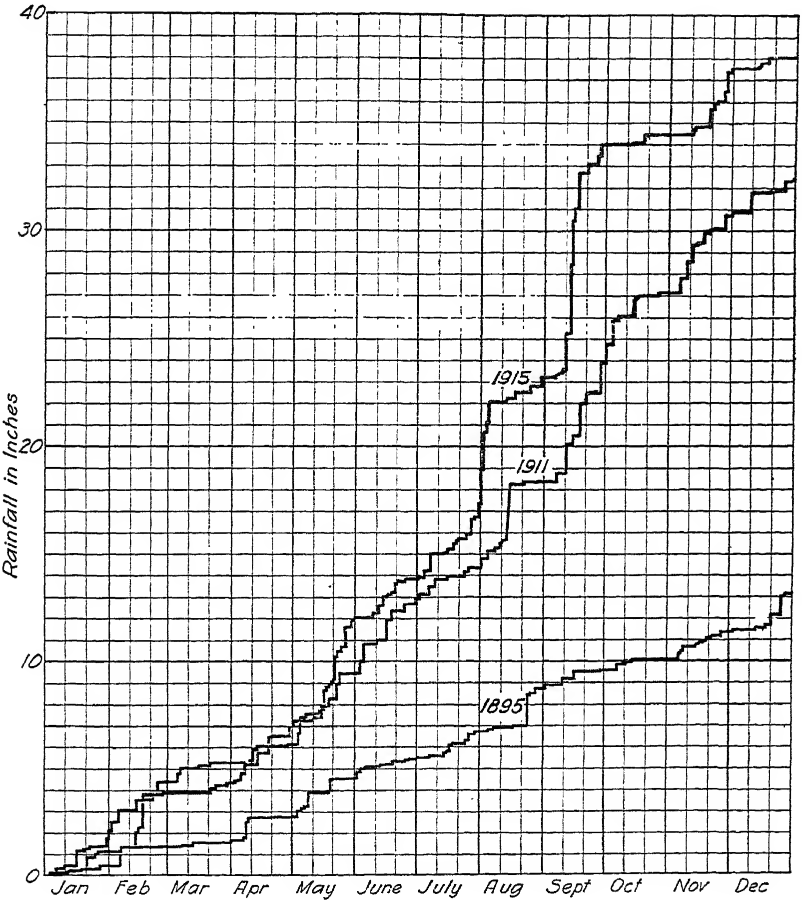

FIG. 131.—Mass Diagrams of Rainfall at Madison, Wis. (see page 236).

The percentage of variation in any monthly period is always very much greater than for the annual period in the same locality. This is very well illustrated by the record of precipitation at Madison, Wisconsin. (See Table 19.) Here the monthly rainfall varies from a minimum of merely a trace (see April, 1877) to a maximum of 10.69 inches (see September, 1915).

115. **Mass Diagrams of Rainfall.**—The seasonal variations as indicated by diagrams of average monthly rainfall are more or less artificial, as rainfall knows no such limitations. The mass diagram, therefore, will give a clearer indication of the actual occurrence and still show its relation to the artificial division of the calendar year. Fig. 130, page 234, shows mass diagrams of the rainfall at various stations throughout the United States for the year 1911, and gives in greater

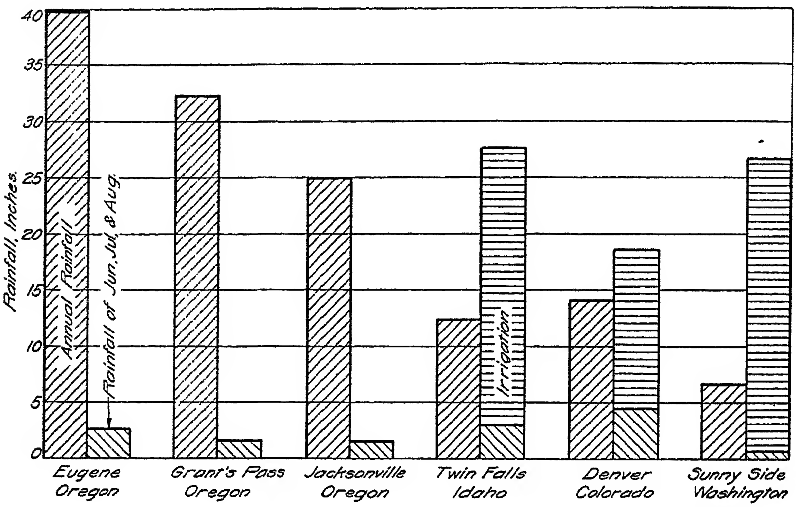

Fig. 132.—Comparison of Normal Annual and Summer Rainfall of Oregon with that of Localities in which Irrigation is Practiced (see page 237).

detail the comparative distribution of rainfall throughout this year. The departure from these typical curves for other years will of course be considerable, but the general character and relative distribution do not vary greatly even though the total for the year is subject to wide variation. Fig. 131, page 235, shows mass diagrams of the occurrence of rainfall at Madison, Wisconsin, for years of maximum, minimum and average rainfall conditions from which variation in the actual rainfall distribution in different years are quite apparent.

116. **Seasonal Divisions of the Year for Agricultural Purposes.**—For agricultural purposes the divisions of time and of rainfall by years and months is not sufficient. Popularly the seasons are divided into:

Spring: March, April, May.
Summer: June, July, August.
Autumn: September, October, November.
Winter: December, January, February.

The shortest day of the year is December 22, and if the change in the earth's temperature followed immediately on the movement of the sun, this date would be mid-winter, and mid-summer would occur on June 22, which is the longest day of the year. The seasonal changes however, lag behind the sun's movements, and the summer months of June, July and August are perhaps the most important from an agricultural standpoint, although the entire period of plant life would in general include April to September inclusive.

As has already been noted (see Sec. 113), the amount of rain that falls in a year is not so important for agricultural purposes as the amount that falls during the growing season. Should this season be deficient in rainfall, water must usually be supplied for successful agriculture by irrigation. In Fig. 132, page 236, a comparison is made of the summer rainfall in certain cities of Oregon, where the annual rainfall is fairly large, with certain locations in the arid regions where irrigation is practiced. It has been found that except in years where a late spring rainfall has stored sufficient moisture in the ground for plant use, irrigation is also essential in Oregon for the best results.

The annual and seasonal averages of rainfall for each State and the normal variation from such averages as determined by the Weather Bureau in 1894[1] are shown in Table 20. These amounts would probably be altered somewhat by the more extensive observations that have been made up to the present time.

In 1897,[2] A. J. Henry made a similar and more extended comparison for many stations in the United States for the crop growing season from April to September, inclusive.

117. Further Analysis of Rainfall for Utilitarian Purposes.—That annual seasonal or monthly quantitative records of rainfall are not in sufficient detail for an intelligent knowledge of its occurrence for utilitarian purposes is obvious from a brief consideration. Hinrich points out ("Rainfall Laws," by Dr. Gustavus Hinrich, U. S. Weather Bureau, 1893) that while the rainfall at Iowa City for 1889 was 28.52 inches in seventy days, and in 1890 was 27.05, in ninety-seven days, the rainfall so expressed might be regarded from such limited data as essentially identical, but that such a statement was not in accordance with facts.

1 Rainfall and Snow of the United States, M. W. Harrington. Bul. C., U. S. Weather Bureau.

2 Rainfall of the United States, A. J. Henry. Report of the Chief of the Weather Bureau for 1896 and 1897.

TABLE 20.

Annual and Seasonal Average of Rainfall for each State.

	Area in square miles.	Spring.	Summer.	Autumn.	Winter.	Annual.	Seasonal variation.
		Inches.	*Inches.*	*Inches.*	*Inches.*	*Inches.*	*Inches.*
Alabama	52, 250	14. 9	13. 8	10. 0	14. 9	53. 6	1. 5
Arizona	113, 020	1. 3	4. 3	2. 2	3. 1	10. 9	3. 3
Arkansas	53, 850	14. 3	12. 5	11. 0	12. 8	50. 6	3. 9
California	158, 360	6. 2	0. 3	3. 5	11. 9	21. 9	40. 0
Colorado	103, 925	4. 2	5. 5	2. 8	2. 3	14. 8	2. 4
Connecticut	4, 990	11. 1	12. 5	11. 7	11. 5	46. 8	1. 1
Delaware	2, 050	10. 2	11. 0	10. 0	9. 6	40. 8	1. 1
District of Columbia	70	11. 0	12. 4	9. 4	9. 0	41. 8	1. 4
Florida	58, 680	10. 2	21. 4	14. 2	9. 1	54. 9	2. 4
Georgia	59, 475	12. 4	15. 6	10. 7	12. 7	51. 4	1. 5
Idaho	84, 800	4. 4	2. 1	3. 6	7. 0	17. 1	3. 3
Illinois	56, 650	10. 2	11. 2	9. 0	7. 7	38. 1	1. 5
Indiana	36, 350	11. 0	11. 7	9. 7	10. 3	42. 7	1. 2
Indian Territory	31, 400	10. 6	11. 0	8. 9	5. 7	36. 2	1. 9
Iowa	56, 025	8. 3	12. 4	8. 1	4. 1	32. 9	3. 0
Kansas	82, 080	8. 9	11. 9	6. 7	3. 5	31. 0	3. 4
Kentucky	40, 400	12. 4	12. 5	9. 7	11. 8	46. 4	1. 3
Louisiana	48, 720	13. 7	15. 0	10. 8	14. 4	53. 9	1. 4
Maine	33, 040	11. 1	10. 5	12. 3	11. 1	45. 0	1. 2
Maryland	12, 210	11. 4	12. 4	10. 7	9. 5	44. 0	1. 3
Massachusetts	8, 315	11. 6	11. 4	11. 9	11. 7	46. 6	1. 0
Michigan	58, 915	7. 9	9. 7	9. 2	7. 0	33. 8	1. 4
Minnesota	83, 365	6. 5	10. 8	5. 8	3. 1	26. 2	3. 5
Mississippi	46, 810	14. 9	12. 6	10. 1	15. 4	53. 0	1. 5
Missouri	69, 415	10. 0	12. 4	9. 1	6. 5	38. 0	1. 9
Montana	146, 080	4. 2	4. 9	2. 6	2. 3	14. 0	2. 1
Nebraska	77, 510	8. 9	10. 9	4. 9	2. 2	26. 9	5. 0
Nevada	110, 700	2. 3	0. 8	1. 3	3. 2	7. 6	4. 0
New Hampshire	9, 305	9. 8	12. 2	11. 4	10. 7	44. 1	1. 2
New Jersey	7, 815	11. 7	13. 3	11. 2	11. 1	47. 3	1. 2
New Mexico	122, 580	1. 4	5. 8	3. 5	2. 0	12. 7	4. 1
New York	49, 170	8. 5	10. 4	9. 7	7. 9	36. 5	1. 3
North Carolina	52, 250	12. 9	16. 6	12. 0	12. 2	53. 7	1. 4
North Dakota	70, 795	4. 6	8. 0	2. 8	1. 7	17. 1	4. 7
Ohio	41, 060	10. 0	11. 9	9. 0	9. 1	40. 0	1. 3
Oregon	96, 030	9. 8	2. 7	10. 5	21. 0	44. 0	7. 8
Pennsylvania	45, 215	10. 3	12. 7	10. 0	9. 5	42. 5	1. 3
Rhode Island	1, 250	11. 9	10. 7	11. 7	12. 4	46. 7	1. 2
South Carolina	30, 570	9. 8	16. 2	9. 7	9. 7	45. 4	1. 7
South Dakota	77, 650	7. 2	9. 7	3. 5	2. 5	22. 9	3. 9
Tennessee	42, 050	13. 5	12. 5	10. 2	14. 5	50. 7	1. 4
Texas	265, 780	8. 1	8. 6	7. 6	6. 0	30. 3	1. 4
Utah	84, 970	3. 4	1. 5	2. 2	3. 5	10. 6	2. 3
Vermont	9, 565	9. 2	12. 2	11. 4	9. 3	42. 1	1. 3
Virginia	42, 450	10. 9	12. 5	9. 5	9. 7	42. 6	1. 3
Washington	69, 180	8. 6	3. 9	10. 5	16. 8	39. 8	4. 3
West Virginia	24, 780	10. 9	12. 9	9. 0	10. 0	42. 8	1. 4
Wisconsin	56, 040	7. 8	11. 6	7. 8	5. 2	32. 5	2. 2
Wyoming	97, 890	4. 3	3. 5	2. 2	1. 6	11. 6	2. 7
Total	2, 985, 850						
Average		9. 2	10. 3	8. 3	8. 6	36. 3	3. 0

"In 1889 there were seven rain days with over one inch and two with over two inches of rainfall; in all, nine rain days with excessive rains, aggregating 13.02 inches. Of the total rainfall of 28.52 inches only 15.50 fell in moderate rains, almost the only ones that can benefit the growing crops.

"In the year 1890 only four rain days exceeded one inch of rain, aggregating 5.88 inches in the entire year. Consequently, of the total rainfall of 27.05 inches, only 5.88 inches came in washing and flooding rains, and 21.17 inches in moderate showers, beneficial to the farmer.

"To be quite exact, we ought yet to separate from these beneficial rains those that were insignificant. In 1889 there were thirty-nine days aggregating only 1.42 inches, while in 1890 there were thirty-five days aggregating 1.15 inches of rainfall."

The comparison of these data with the twenty-year normal for Iowa City is shown in Table No. 21.

TABLE 21.

Year	1889	1890	20 Yr. Normal
Total Rainfall	28.52	27.05	35.59
Washing & Flooding Rain (1 in. or more per day)	13.02	5.75	15.69
Insignificant Rains	1.42	1.15	1.45
Total Useless or Damaging Rains	14.44	7.03	17.14
Total Utilizable Rain	14.08	20.02	18.45

From the above it will be noted that so far as they came in the right seasons for agriculture, the utilizable rains of 1890 exceeded the normal, although the annual rainfall was over eight inches sub-normal.

TABLE 22.

Hinrich's Classification of the Intensities of Rainfall.

Type	Amount	Degree
0	.01 to .1	Sprinkles or Insignificant Rains.
		Useful for Grass, Grain and Corn.
1	.1 to .2	Showers.
2	.2 to .4	Light Rains.
3	.4 to .8	Soaking Rains
		Excessive or Damaging Rains.
4	.8 to 1.6	Washing Rains.
5	1.6 to 3.2	Flooding Rains.
6	3.2 and up	Torrential Rains.

118. **Seasonal Rainfall as Affecting Stream Flow.**—In considering the rainfall on a district in relation to the runoff of streams, it is desirable to study the rainfall records on the basis of what may be termed "the water year." This period will vary somewhat materially with the climatic conditions in various parts of the world. In England, the water year September 1 to August 31 is sometimes used. The United States Geological Survey is at present (1917) arranging their runoff data for a water year from October 1 to September 30. Rafter[3] has used a water year from December 1 to November 30. He calls the first six months of this period, December to May inclusive, the "storage" period. June, July and August constitute the "growing" period; September, October and November, the "replenishing" period. For the purpose of discussing rainfall in its relation to runoff it is desirable to divide the annual rainfall in accordance with such periods as may be selected for such purposes. For example, from a study of mass diagrams of the annual rainfall at Madison, Wisconsin, the water year might be divided as shown in Table 23.

TABLE 23.

Logical Division of the Water Year at Madison, Wisconsin.

WATER YEAR	FROM	TO
1903– 4	Oct. 3, 1903	Sept. 28, 1904
1904– 5	Sept. 28, 1904	Oct. 17, 1905
1905– 6	Oct. 17, 1905	Oct. 17, 1906
1906– 7	Oct. 17, 1906	Sept. 16, 1907
1907– 8	Sept. 16, 1907	Sept. 27, 1908
1908– 9	Sept. 27, 1908	Sept. 12, 1909
1909–10	Sept. 12, 1909	Sept. 22, 1910
1910–11	Sept. 22, 1910	Sept. 28, 1911
1911–12	Sept. 28, 1911	Sept. 13, 1912

For small drainage areas in the immediate vicinity of Madison to which these mass diagrams of rainfall might apply, a similar division of stream flow data might be made although the year for such data might logically be started a few days later as the effect of rainfall on stream flow is not immediate. For large areas where the rainfall differs materially from place to place a combined mass diagram will give a clear idea of the actual variations in the beginning of the water year.

The artificial divisions of daily, weekly, monthly and other periodic arrangements of observations are sometimes misleading when they

[3] Hydrology of the State of New York. G. W. Rafter, Albany, 1905.

are examined with reference to the value of the rainfall so recorded for agricultural purposes or with reference to stream flow records. A rainstorm follows no such divisions of time, and the effect of a heavy rainfall near the end of a period will often result in an increased runoff during the following period for which monthly records of observations, usually available, offer no adequate explanation. This misleading feature of the records of artificial periods should be duly recognized; and for the purpose of detailed hydrological analysis, the seasons may better be divided up in accordance with the actual occurrence of the rainfall than on the basis of any artificial division of the calendar year.

In the study of runoff attention must also be given to the amount and intensities of occurrence of the rain. Showers and light rains (see Table 23) will ordinarily not affect runoff conditions or even the ground water during the growing season, as they will ordinarily be taken up entirely by vegetation when such exists on the drainage area, while such rains will augment the stored waters of the winter season. For a comparison of rainfall with the runoff from year to year such rainfalls may be eliminated from consideration, either from the seasonal amounts or from the mass curves. In certain studies in Wisconsin, of rainfall in relation to runoff, single rain storms not less than the following amounts were eliminated for various months as follows:

November	.08 or less
Dec., Jan. and Feb.	all considered
March and April	.10 or less
May	.15 or less
June and September	.20 or less
July and August	.25 or less
October	.12 or less

The net effect on the annual amounts of rainfall which under the above assumptions might be considered as actually influencing stream flow or ground storage is shown in Table 24.

TABLE 24.

Effect on Annual Rainfall of the Elimination of Showers and Light Rains.

Year	Actual Rainfall	Estimated Effective Rainfall	Percentage Considered
1904	34.69	27.82	80
1905	30.46	24.96	82
1906	33.96	28.85	82
1907	24.93	18.36	73
1908	28.29	22.81	81
1909	30.70	24.14	79
1910	21.01	16.20	77
1911	38.91	31.49	81
1912	29.88	22.99	76
1913	30.72	21.75	71
1914	30.40	20.25	68
1915	32.91	26.78	82

CHAPTER XI

GREAT RAINFALLS

119. Importance of the Study of Great Rainfalls.—Many engineering problems, such as flood protection, the size of sewers, drains and ditches for drainage works, the size of spillways and flood gates in dam and other similar engineering projects that are affected by the possible maximum flow in streams or from drainage areas of greater or lesser extent, are often dependent for their proper solution upon a knowledge of the intensity and distribution of the maximum rainfalls that must be expected and the flood flow that will result therefrom. While the flood volumes in all such cases depend on many factors, the most important one is the amount of the rainfall that may occur on the area under consideration within a given period of time.

The actual maximum runoff from a given area is always the best information to be used as a basis for the solution of such problems. Such knowledge is seldom available because runoff data are seldom collected until a need for such information arises, when on account of the rarity of occurrence of extreme conditions the needed information cannot be secured immediately, and the problem must often be solved without undue delay. Rainfall statistics for a considerable period of time and of more or less value for the solution of such problems are usually available at nearby stations or at stations where the conditions are sufficiently similar to warrant conclusions based on the same. A study of such records therefore often becomes essential, and it is desirable that such a study be based on a proper interpretation of the records and a knowledge of the ordinary, the occasional and the rare but extreme conditions that are certain to occur.

120. Great Rainfalls.—The comparative magnitude of a rainfall will depend on three factors, each one of more or less relative importance, according to the nature of the problem which is under consideration. These factors are: *intensity, duration* and *area* covered by the rainstorm.

Intensity refers to the rate of precipitation or the amount of rain falling within a given time. *Duration* defines the time limit within which the precipitation takes place, and *area* defines the geographic extent of the storm or of as much of it as may be covered by the rains of given intensity and duration.

For example, Mr. James B. Francis investigated in some detail the great storm that occurred in New England on Oct. 3–4, 1869.[1] He found that some of the local rates of intensity and duration were as follows:

TABLE 25.

Local Intensity and Duration of Rainfall of Oct. 3–4, 1869.

Amount	Duration	Rate per 24 Hours
4.00 inches	2 hours	48.00 inches
4.27 inches	3 hours	34.16 inches
5.86 inches	18.5 hours	7.61 inches
7.15 inches	24.0 hours	7.15 inches
8.90 inches	30.0 hours	7.13 inches
12.35 inches	48 hours	6.17 inches

He also found that the total amount of rainfall and the extent of area covered by the storms were as follows:

TABLE 26.

Amount and Distribution of the Rainfall of Oct. 3–4, 1869.

Depth of Rain	Area Covered
6 in. or more	24,431 sq. mi.
7 in. or more	9,602 sq. mi.
8 in. or more	1,824 sq. mi.
9 in. or more	1,046 sq. mi.
10 in. or more	519 sq. mi.
11 in. or more	179 sq. mi.

Another factor which may be of great importance in certain problems is *frequency*. Frequency defines the period of time within which a rainfall of a given magnitude may be expected to occur. Experience has shown that the most excessive rainfalls occur only rarely, for brief intervals and over limited areas, and that as the size of the area and the length of time considered increase, the magnitude of that which must be regarded as excessive rainfall on such areas diminishes. The probability that a more excessive rainfall may occur in the future and the determination of the frequency of occurrence of storms of any magnitude are to a considerable extent dependent upon the length of the record and may be treated on the basis of probabilities as described for annual rainfall in Sections 110 and 111.

Experience has also shown that the probability of the occurrence of great rainfalls is largely a local problem and that the causes and con-

[1] James B. Francis. Distribution of Rainfall during the Great Storm of October 3 and 4, 1869. Trans. Am. Soc. C. E., Vol. 7, p. 224.

ditions of rainfall vary to such an extent that the nature of the extreme rainfalls which should be anticipated in one part of the country may be greatly different from those which may occur in some other parts of the country, where the factors that control their occurrence are quite different. Like most other rainfall problems, the problem of the occurrence of great rainfalls must be solved on the basis of our limited knowledge of the nature of the rainfalls that have occurred in the past, either in the same locality or in other localities where similar conditions exist and on the assumption that conditions which have obtained in the past will again be repeated and perhaps exceeded in the future.

121. **Limitations of Information.**—There are about 4,700 Weather Bureau Stations in the United States, approximately equivalent to one station for each 632 square miles. These stations are more numerous in the thickly settled portion of the country and with few exceptions are located at or closely adjoining centers of population. There are few stations on mountains or deserts or other uninhabited regions. As a consequence of these conditions there are large regions from which practically no information is available except such as may be inferred from the records of adjoining stations.

With rain gages scattered at such wide intervals as obtain in even the most thickly populated portion of the country, rainfalls of high intensity but of limited area undoubtedly frequently occur of which no records are made, as the area covered is largely or entirely between stations. For example, a considerable flood occurred about June 4, 1916, on Mad Creek about six miles south of LeRoy in western New York.[2] The drainage area of the stream was only 1.5 square miles, and the maximum flood discharge was estimated at about 2,000 cubic feet per second per square mile, a most unusual flood discharge. As the slopes tributary to this stream are not particularly steep, it is probable that such a flood peak would have required a rainfall on the drainage area of 12 or more inches in 24 hours, in order to have produced the maximum peak. No indication of such a rainfall is shown in the rainfall records. The nearest rainfall station of the U. S. Weather Bureau at Avon, New York is about ten and one-half miles east of this area and shows a rainfall for June 2 and 3 of 2.58 inches.

The small area to which many intense storms may be limited is illustrated by Fig. 133, page 231,[3] which shows a ninety minute pre-

[2] See letter from J. P. Wells. Eng. Rec., June 24, 1916, Vol. 72, p. 842.

[3] See The Ohio Water Problems. C. E. Sherman. Bul. No. 15, College of Eng. Univ. of Ohio.

cipitation that occurred near Cambridge, Ohio, July 16, 1914. This storm chanced to center over the U. S. Weather Bureau Station which is located outside of Cambridge. The observer was ready and made an accurate measurement of the precipitation, and soon after the storm the County Surveyor traced its outline upon the Cambridge quadrangle of the U. S. Topographical Survey. In drawing the map (Fig. 133) it was assumed that the outline traced represented a rain-

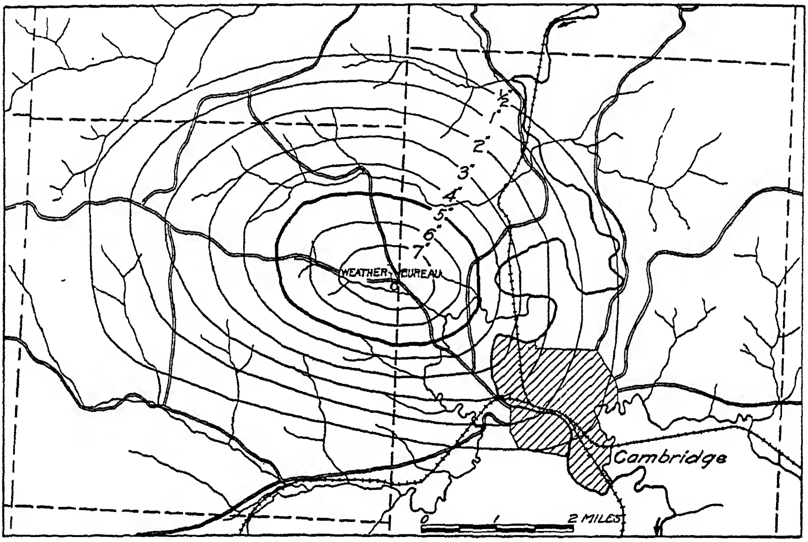

FIG. 133.—Rainfall in Ninety Minutes at Cambridge, Ohio.

fall of one-half inch, and the isohyetal lines were proportioned between the outline and the station. It should be noted that if the center of this storm had moved five miles in any direction, there would have been no adequate records to give any idea of the intensity, and if the center had moved two miles its maximum intensity would not have been recorded within 25 per cent. or more.

On August 24, 1906, an unprecedented rainfall occurred at Guinea, Caroline County, Virginia, with an intensity of about 9.25 inches in about thirty minutes. This rain accompanied a local thunderstorm confined to a limited area. The storm passed over Woodslane, Va., about 4 P. M. and the rain at Guinea, about two and five-tenths miles from Woodslane, began about 5:30 P. M. and continued for an hour, accompanied by heavy thunder and lightning. The storm afterward turned northeastward and passed over Corbin, Va., about six miles from Guinea. It was not noted at other points, and the territory cov-

ered was apparently not more than ten miles in length. The storm did not reach any Weather Bureau station.[4]

It is apparent from the above discussion that many local rain storms, especially such as occur in the mountains, deserts or thinly inhabited portions of the country, are entirely unrecorded and that our information concerning intense storms which cover only small areas is very incomplete.

Table 27, page 248, shows the record of the most intense rainstorms that have been observed in the United States and elsewhere so far as could be determined from available records.

122. **Sources of Information.**—Unfortunately the rain gages in use in the majority of the stations in the United States are the gages shown in Fig. 106 and only furnish information of the rain that has fallen during the period which has elapsed since the gage was last read. By reading at frequent intervals, the rate of rainfall for brief periods may be determined, but in general observations are made only once for each twenty-four hours, and hence the information available from such gages is usually only for such period. As intense twenty-four hour rainfalls seldom occur within the time included between two readings, even the most intense rainfall that occurs at a station for such a period is not always ascertainable from the records unless special measurements are made and noted at the time of the occurrence. For example, in the heavy rainfall that occurred in July, 1916, near Altapass, North Carolina, (see Fig. 96, page 175) the records show that the rainfalls on July 15 and 16 were 3.90 and 19.32 inches respectively. It was noted however that the maximum precipitation in twenty-four hours included the rainfall on a part of both of these days and amounted to 22.22 inches, one of the greatest rains that has ever been recorded within twenty-four hours in the United States.

Fortunately, recording gages are now in use at nearly 400 of the principal Weather Bureau Stations, and many records are available for a considerable term of years from these various stations. Such records as are available have for the most part been published in the Monthly Weather Review, to which reference must be made for such data. When considering storms of a greater duration than twenty-four hours, the records of daily rainfall become of value; but here again some uncertainties arise from the different times at which the gages are read, and from such records it is impossible to differentiate the rainfall for any periods of less than one or more days, and even

[4] Monthly Weather Review, 1906, p. 406.

TABLE 27.—*Local Rainfalls of High Intensity.*

DEPTH IN INCHES.

Station.	Location.	Length of Record. Yrs.	Date of Occurrence.	PERIOD OF TIME. 5 Min.	10 Min.	30 Min.	60 Min.	90 Min.	24 Hrs.	48 Hrs.	72 Hrs.	1 Year.	Source of Data.
Alexandria	La.	27	Jun. 14, 1886						21.4				U.S.Mon.Weather, Rev. Jul 1912, p. 1062.
Altapass	N. C		Jul. 15, 1916						22.22				U.S.Mon.Weather. Rev. Jul. 1916
Bonaparte	Iowa		Jun. 10, 1905						12.10[9]				Iowa Weath and Crop Service, June 1905
Buck Springs	N. C		1906									129.10	U.S.Mon.Weather, Rev.
Cambridge	Ohio	23	Jul. 16, 1914					7.09					U. S. Climatological Data, Jul. 1914
Campo	Cal		Aug. 1891.				11.5						Hann. Lehrbuch der Meteorologie, p. 375
Donaldsonville	La.	27	Apr. 1911–Mar. 1912									142.5	U. S. M. W. R.. Jul. 1912, p. 1062
Ft. Clark	Tex.		June 14, 1899						18.0[7]				U. S. M. W. R. June 1899
Ft. Myers	Fla	15							11.70	12.15	13.07	69.65	District Weather Bureau
Galveston	Tex.	42			3.94[1]				13.93				U. S. M. W. R. Oct. 1913
Glenora	Ore.	24	1896									167.29	U. S. M. W.R. Jul. 1912, p. 1062
Guinea	Va.		Aug. 24, 1906			9.25							U. S. M. W. R.Aug. 1906
Jupiter	Fla	17		0.57	1.10	2.55	3.83	4.59					District Weather Bureau
Kansas City	Mo.	27	Aug. 23, 1906	0.57	1.12	3.07	4.74	5.60					U. S. M. W. R., Aug. 1906, p. 398
Keosauqua	Iowa		Jun. 10, 1905						11.09[8]				Iowa Weath and Crop Service, June 1905
Key West	Fla	45		0.60	0.93	1.87	3.35	5.28[2]					District Weather Bureau
Los Angeles	Cal	39		0.36	0.66	1.12	1.51	1.84	5.12				U. S. M. W. R., Jun. 1914
Montell	Tex.		June 28, 1913						20.60[5]				U. S. M.W. R. June 1913, p. 908
Madison	Wis.	48	Aug. 8, 1906	0.55	1.08	2.09	3.61	4.69				52.91	U. S. M. W. R. Aug. 1906
Matagorda	Tex.		Apr. 30-May 1, 1911						15.71				U. S. M. W. R. Jul. 1912
Merrill	Wis.	10	Jul. 24, 1912						11.25	10.60	14.14		U. S. M. W. R. Jul. 1912
Miami	Fla	10		0.50	0.75	1.56	2.64	3.48[2]	9 00			85.36	District Weather Bureau
Palmetto	Nev		Aug. 1890				8.82						Hann, Lehrbuch der Meteorologie, p. 375
Philadelphia	Pa	44	Aug. 3, 1898	0.60			3.82	5.43[3]					Hann, Lehrbuch der Meteorologie, p. 375
St. Louis	Mo.	43					5.04		6.17				Hann, Lehrbuch der Meteorologie, p. 375
Stockport	Iowa		Jun. 10, 1905						10.63	7.67	10.19		U. S. M. W. R.
Tampa	Fla	17		1.00	1.50	2.45	3.13	3.50[2]	4.40			63.82	District Weather Bureau
Turnersville	Tex.										33.+[6]		U. S. M. W. R. June 1899
Balboa	C. Z	8		0.90			5.86		7.57				Rep. Isthmian Canal Com. 1914 p. 146
Gatum	C. Z	7		0.62			3.82		10.48				Rep. Isthmian Canal Com. 1914 p. 146
Porto Bello	C. Z	6		2.48			4.53		10.86		114.9[4]		Rep. Isthmian Canal Com. 1914 p. 146
Cherrapungi	India								40.8	50.0		905.1	Hann, Lehrbuch der Meteorologie, p. 372
Tanabe	Japan		Aug. 1889				3.57		35.5	50.79	61.58		Hann, Lehrbuch der Meteorologie, p. 372
Crohamhurst	Queensland		Feb. 1893						30.71				Hann, Lehrbuch der Meteorologie, p. 372
Joyeuse	France		Oct. 1827						30.7				Hann, Lehrbuch der Meteorologie, p. 372
Maui	Hawaii		Apr. 16, 1895						21.14				Hann, Lehrbuch der Meteorologie, p. 373
Neuwiese	Austria		Jul. 29, 1897						13.58				Hann, Lehrbuch der Meteorologie, p. 372
Calcutta	India		May 1, 1835						12.01				Hann, Lehrbuch der Meteorologie, p. 372
Molitg	E. Pyrenees		May 20, 1868				8.23	12.32					Hann, Lehrbuch der Meteorologie, p. 373
Seathwaite	England		Nov. 12, 1897						8.03				Hann, Lehrbuch der Meteorologie, p. 373
Preston	England		Aug. 10 1893	1.24									Hann, Lehrbuch der Meteorologie, p. 375
Basel	Switz		Jul. 28, 1896	0.88			2.09						Hann, Lehrbuch der Meteorologie, p. 375

[1]14 min. [2]120 min. [3]75 min. [4]5 days. [5]18.5 hours. [6]90 hours. [7]21,5 hours. [8]10.09 in. in 12 hours [9]Approx. 11 in. in 8 hours.

then when comparing stations where the time of reading is different, they are to an extent uncertain. Such a study, when it includes all of the data which are pertinent to a given locality, will furnish a reasonable basis for the estimate of local storm intensity.

123. **Frequency of Intense Rainfalls.**—In general the frequency of intense rainfalls increases with the increase in the average annual rain-

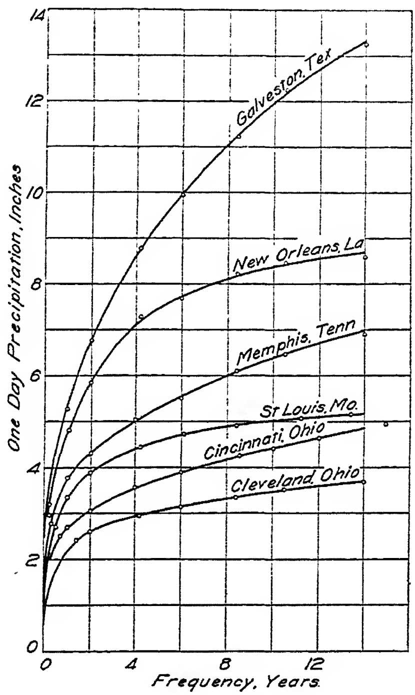

Fig. 134.—Average Frequency and Average Intensity of Maximum One Day Storms (see page 250).

fall of a locality for the reason that the conditions favorable to intense rainfall are more common under such conditions. For example, intense rainfalls are much more common in the State of Florida where the average rainfall is about 55″ per annum than in the state of Wisconsin where the average rainfall is about 32″ per annum, or in the State of Ohio where the average rainfall is about 36″ per annum.

This condition is due however not only to the conditions favorable for rainfalls in Florida but also to the West Indian hurricanes which frequently cross that State and which commonly bring about conditions favorable for torrential rainfall. The rainfalls of Wisconsin

and Ohio are a result of the greater cyclonic storms which in general are not so productive of brief and intense precipitation. Occasionally, however, conditions favorable to high rates of precipitation do occur in Wisconsin and Ohio as is evidenced by the intense rainfall of July 16, 1914, shown in Fig. 133, page 246, and by the rainfall of 11¼″ which occurred at Merrill, Wisconsin, within twenty-four hours in July, 1912.

In the semi-arid regions where the average annual rainfall is very low, exceedingly intense rains of limited extent, termed cloud bursts, occasionally occur. On August 9 to 11, 1909, 13.38″ of rain fell at Monterey, Mexico, within forty-eight hours, and between August 25 and 29, 1909, 21.61″ of rain fell within ninety-eight hours. The annual rainfall at this station for 21 years previous to that date averaged 19.86″, and in the four days of the second storm more water fell than usually falls in an entire year.[5] It is evident therefore that the intensity of the local rainfall which may occur bears no direct relation to the amount of annual precipitation.

Figure 134,[6] page 249, is a study of the average frequency and average intensity of the occurrence of one-day storms at various selected stations where long records, ranging from forty-two years at Galveston to sixty-seven years at St. Louis, were available. These curves are constructed as follows: For the Galveston curve, based on forty-two years of record, the probable maximum storm that will occur each year is taken as equal to the average of the forty-two maximum storms that have occured during the period, and the average of the twenty-one maximum storms is taken as the probable maximum storm that will occur every second year. Other points on the curve are established in the same manner.

The flattening of the curves, due to the close agreement in intensity of the several storms in the records which are included in the average for the fourteen year period, gives assurance that the curves are typical, and that the probabilities that a storm such as is likely to occur at Galveston may occur at Cleveland are very remote if not physically impossible.

124. **Local Intensities of Short Duration.**—The records of intense storms of short duration for any locality may be platted with the intensities as ordinates and with the intervals of time at which such in-

[5] See Eng. News, Sept. 23, 1909.

[6] From data furnished by A. E. Morgan, Chief Engineer, Miami Conservancy District. See also Eng. News, Vol. 77, p. 150.

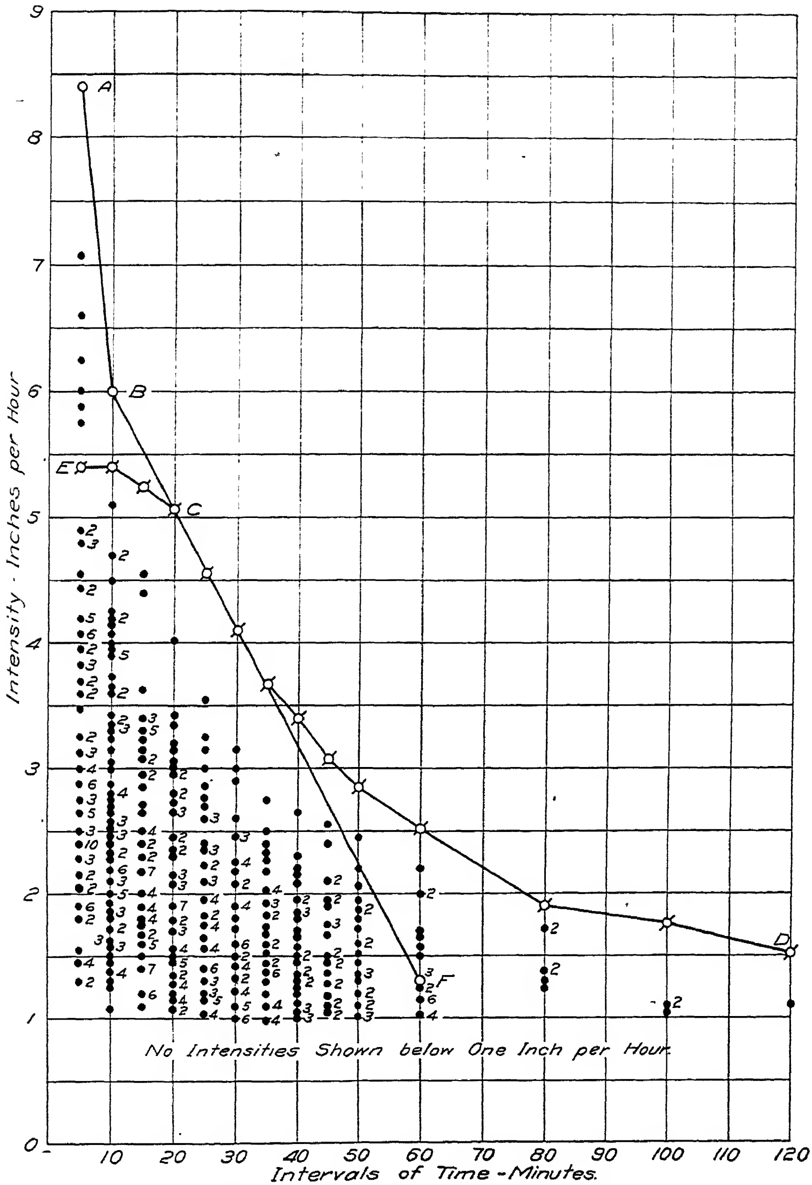

FIG. 135.—Maximum Intensities of Rainfall at St. Paul, Minn.

tensities have occurred as abscissas. Such a graphical chart of the intensities of rainfalls which have occurred at St. Paul, Minnesota, within the last 29 years (1917) is shown in Fig. 135. The intensi-

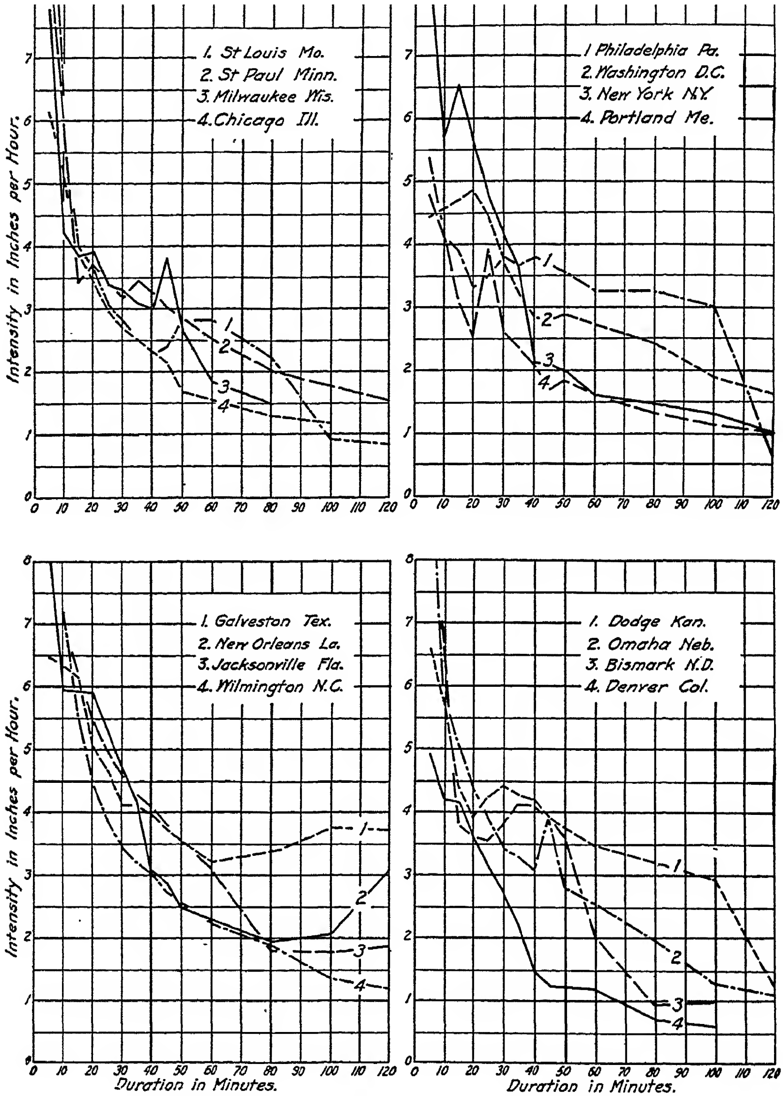

FIG. 136.—Maximum Rates of Local Rainfalls (see page 253).

ties investigated are those of one inch per hour or greater and for intervals of from 5 to 120 minutes. The enveloping line, ABCD, drawn through the points of maximum intensity for each interval, shows the absolute maximum experiences of St. Paul within the period for which the records are available. Each of the points shown is the maximum

rate for the given interval for a storm in which a rate greater than one inch per hour has occurred for such interval, and in some cases one point under each interval may represent a single storm. Thus the line ECD is the intensity-interval curve for the storm of August 9, 1902, and the line ABF is the intensity-interval curve for the storm of June 15, 1892. These two storms together furnish the maximum records for the intensities at St. Paul, while numerous other storms of lesser intensities are represented by the other points on the diagram. In some cases a single storm may be represented by only one point. Where the same intensity of rainfall has occurred two or more times at any one interval, the fact is designated by a number set opposite the point in question.

Fig. 136, page 252 shows the maximum rates of local rainfalls of short duration for various localities throughout the United States, determined in the same way but covering the period from 1889 to 1910 inclusive.

125. Frequency of Intense Storms of Short Duration.—It will be noted that the envelope ABCD (Fig. 135, page 251) is drawn through points that are for the most part some distance above the next highest points and therefore seems to represent conditions somewhat more extreme than should normally be expected for a 29-year period. In some cases the extreme storms seem to represent conditions even more unusual when the limited period of observation and the more frequent intensities are considered. Thus in Fig. 137, page 254, where the intensity of storms of brief duration at Madison are shown, the storm of August 29, 1906, is so far above the storms indicated by the remaining points as to show clearly that it is not a fair criterion of the limiting intensities which should ordinarily be expected to occur within the 13 years of record (1905–1917). The unusual character of this rainfall is also indicated by the comparison shown in Fig. 141, page 258.

Referring again to Fig. 135, showing the record of intense storms at St. Paul, if the various intervals are considered it will be noted that there are two storms of one inch per hour or more at the 120-minute interval or $\frac{2}{29} = .069$ storm per year of a greater intensity than one inch per hour. At the interval of 100 minutes there are four storms above one inch per hour intensity or a frequency of .138 storm per year, etc., for each interval. In the same way the storms per year greater than 1.5 inch, 2 inches, 2.5 inches, etc., per year may be determined and

platted as in Fig. 138, page 255. These points may be connected by straight lines thus indicating the absolute results of experience; or a series of smooth curves can be platted through these points which may

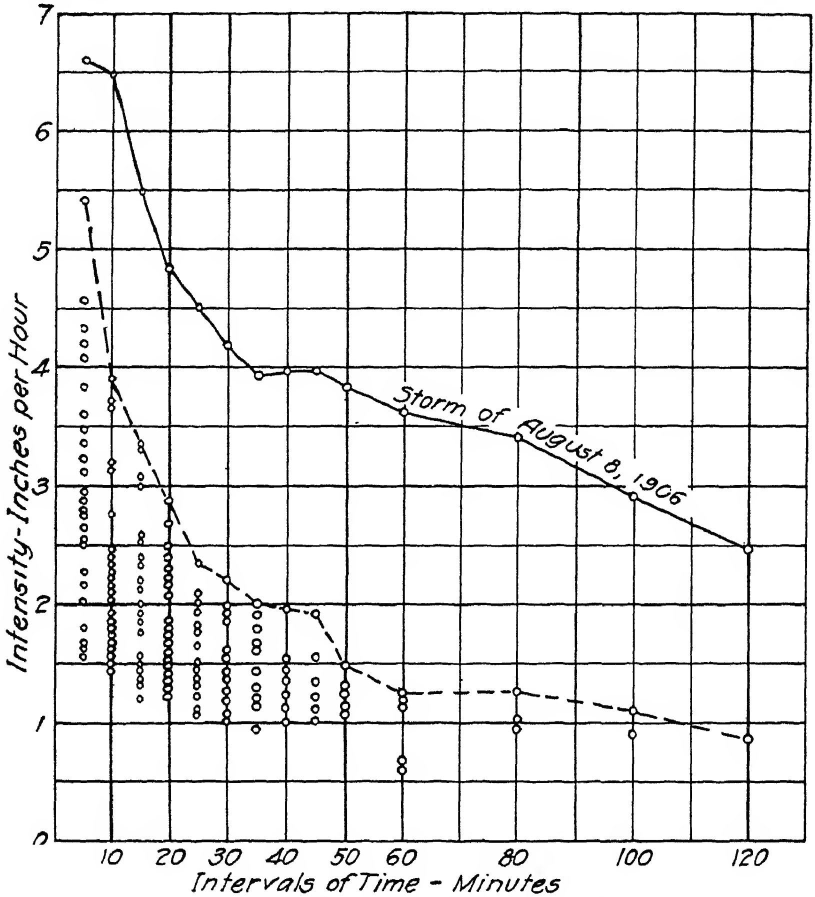

FIG. 137.—Intensities of Storms of Short Duration at Madison, Wis. (see page 253).

be drawn to average the points or to include them all, as the investigator may desire. In the case of the smooth curves the indication of frequency at certain intervals may be somewhat greater or less than the absolute experience, but if consistently drawn may possibly indicate more nearly the truth which would be developed by a longer series of observations, by giving greater weight to the preponderance of evidence over a single or a few observations which may be more or less extreme.

Having platted the points as above outlined and adjusted the frequency-interval lines as indicated, it is obvious that a horizontal line through the frequency of one storm per year will indicate by its intersections with the various curves, the intensity which must be expected each year at the various intervals of time. It must also be noted that

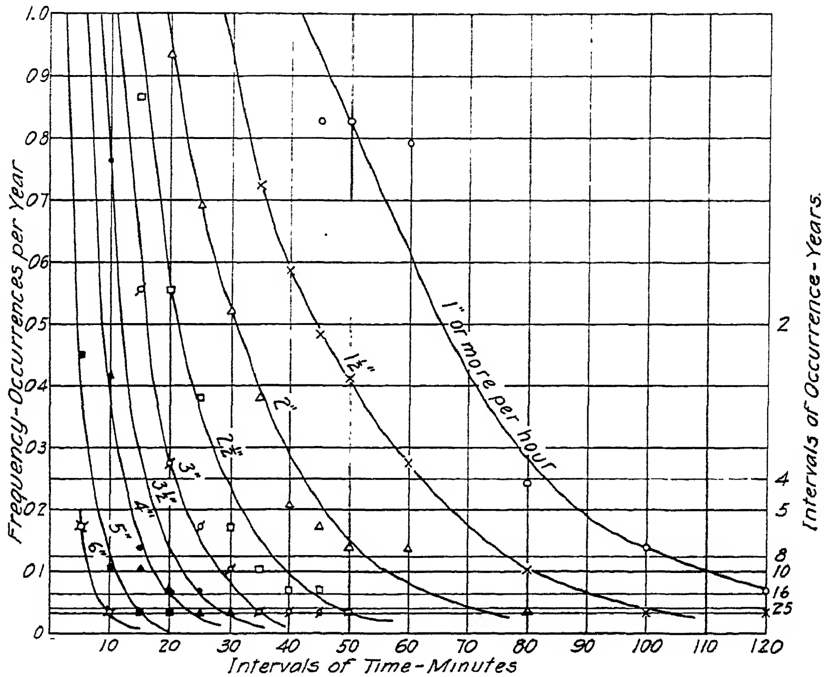

FIG. 138.—Frequency of Intense Rainfalls at St. Paul, Minn. (see page 254).

the intensity at the various intervals of time for any other term of years can be determined in the same way by the intersection of these curves by a horizontal line drawn through a point below the frequency of one storm per year determined by dividing one by the number of years for which such curve is desired, as indicated in Fig. 138. Such curves determined for St. Paul are platted in Fig. 139, page 256.[7] These curves indicate a certain general progressive distribution which gives at least

[7] This general method for determining frequency curves is that outlined by Metcalf and Eddy under the heading of "Frequency of Heavy Storms." They have also discussed "Intensity of Precipitation" at considerable length. See "American Sewerage Practice," by Metcalf and Eddy, Vol. 1, pages 220 to 234.

some indication of the probable frequency of the maximum curve first developed in Fig. 135, page 251.

By platting interval curves in terms of intensity and years of occurrence as determined from Fig. 139 (see Fig. 140), and extending these curves beyond the limits of experience (shown by dotted lines), an estimate can be made of the probable limiting time of the maximum curve which, as shown in Fig. 140, may be estimated as representing a

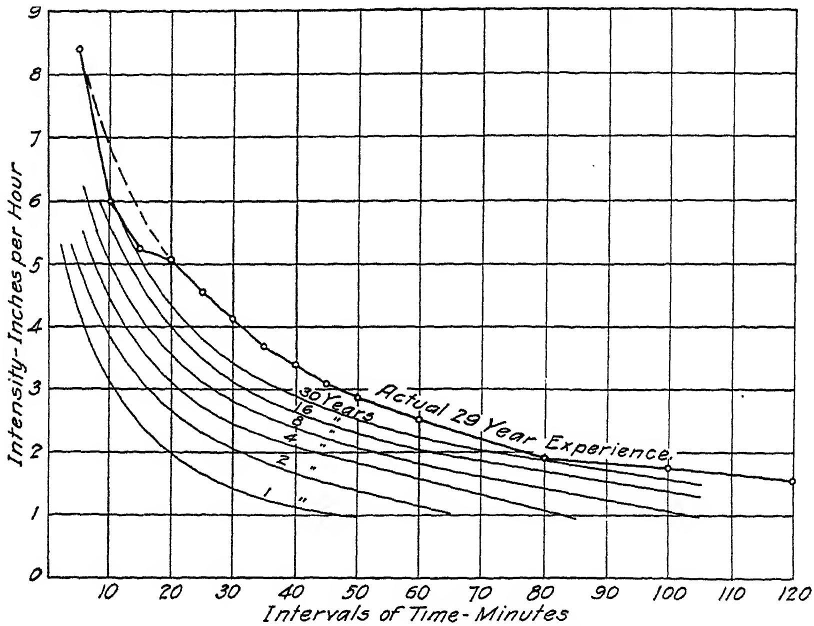

FIG. 139.—Intensity of Rainfall at St. Paul for Various Frequencies (see page 255).

probable frequency of once in from 90 to 120 years. As previously noted, however, any attempt to extend actual experience beyond the term of years in which such experience is acquired is speculative and must be taken as indicative only and not as in any sense established.

It is important that the engineer should also recognize the limiting value of the frequency investigation above outlined. With the present knowledge available, it furnishes perhaps the best basis for the study of this subject. Like the investigation of the annual rainfall at Boston, discussed in Sec. 110, a similar investigation for a similar period of years in any given locality would doubtless give quite different conclusions as to frequencies.

It should also be noted that the rates of rainfall used in the investigation, especially for the longer intervals of time, are average rates and not uniform rates, and are therefore somewhat misleading when these longer intervals are considered. For example, the actual occurrence of the rainfall of August 8 and 9th, 1906, at Madison is shown in Fig. 141 with the uniform rates of occurrence platted below and the average

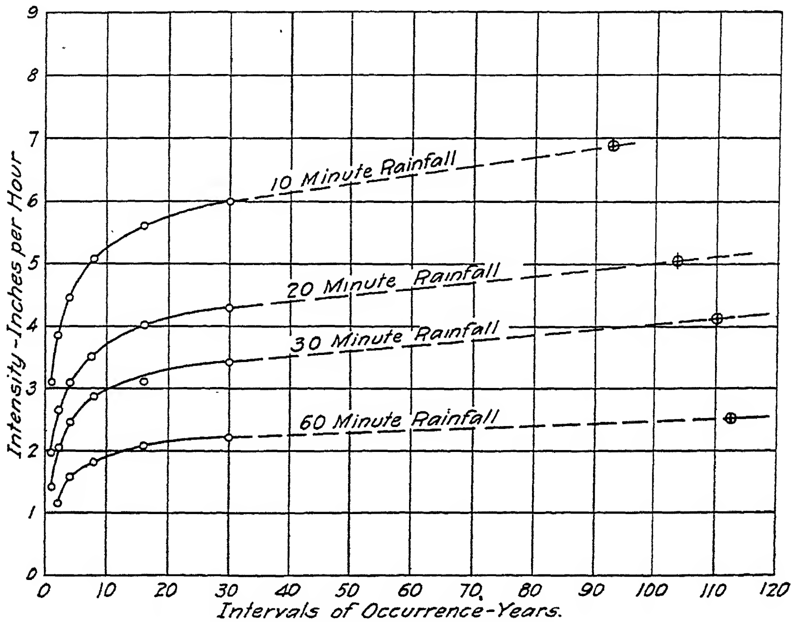

FIG. 140.—Expectancy of Maximum Rainfall Occurring at St. Paul.

rates previously shown platted above. In the use of such data as a basis of engineering design, it is therefore essential that while taking all possible advantage of the general methods of investigation above outlined, the engineer should also study the actual manner of occurrence of maximum storms which his designs must take into account.[8]

126. Approximate Maximum Intensities of Short Storms.—A brief study of intense rainfalls indicates that the limited time for which records are available at any one station is not long enough to give the maximum rates which are liable to occur at that station in the course of time. If the intensities at various stations in the same meteorological

[8] Long Time New York Rainfall Records, by O. Hufeland. Eng. News. Vol. 76, p. 450, Aug. 31, 1916.

district are investigated, it is found that certain stations will show extreme conditions for certain intervals, while for other intervals extreme conditions are found to have occurred at other stations. For such districts there seems to be no reason why, in the lapse of time, storms of

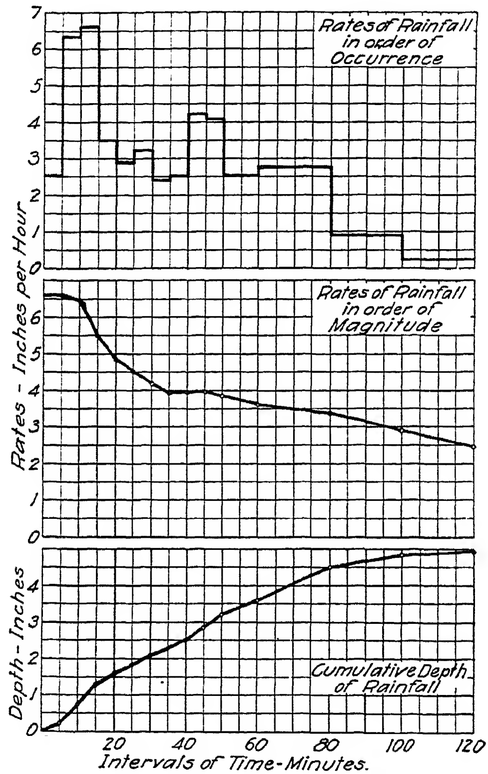

FIG. 141.—The Intensity of Rainfall Occurring August 8, 1906, at Madison, Wis. (see page 253).

similar intensity may not occur at any or all other stations in such district. If therefore the maximum rates of local rainfall at the various stations in a given district are determined for the period covered by the records, are then platted on one diagram, and a smooth enveloping curve is drawn through the maximum points shown by the local curves, such curves may be regarded as the maximum rate curve for the district, based on the combined experience of its local stations. Such a curve does not represent the extreme maximum which may occur, for such extreme conditions may never have been experienced at any of the

stations. Such a curve may perhaps be regarded as an experience curve of two or more times the length of the average record involved. It furnishes important limiting rates, the frequency of which cannot definitely be evaluated. It will be exceeded only at very rare intervals.

In a study of the probable maximum rates of local rainfall for Wisconsin conditions, maximum rates of local rainfalls were investigated and curves of maximum intensity were made for various stations as shown in Fig. 142. From this diagram it will be noted that for intervals of 5 and 20 minutes, the intensities at St. Paul were maximum; and for intervals of 10 and 15 minutes and for all other intervals from 30 to 120 minutes, intensities at Madison were materially above those at any other station. The envelope ABCDE, therefore, seems to indicate the experience of extreme intensities for short duration for Wisconsin.

In this same manner various studies have been made of the extreme local intensities at various points.

127. **Studies of Local Intensity.**—One of the early studies of the intensity of local rainstorms was made by Professor A. N. Talbot[9] in 1891. Talbot platted all available records of local rainfall from all the stations in certain groups of states where he considered the conditions were similar, and drew certain curves to show the ordinary limits of "ordinary maximum rainfall" and of "rare rainfall."

Fig. 143, page 261, shows Talbot's study of the rates of rainfall in the Northern Central States. The lower curve, which he terms "the curve of ordinary maximum rainfall" is represented by Equation 1

$$i = \frac{1.75}{T + .25} \qquad (1)$$

The upper curve he terms "the curve of rare rainfall" which is represented by Equation 2

$$i = \frac{6}{T + 0.5} \qquad (2)$$

In these formulas *i* is the rate of rainfall in inches per hour for the time *T* expressed in *hours*. The points on the diagram represent the actual records of individual storms. It will be noted that the curve of rare rainfall has sometimes been exceeded.

A number of attempts have been made to express mathematically the intensity of rainfall with respect to time. The results of some of the

[9] Rates of Maximum Rainfall. A. N. Talbot. Technograph 1891–92, p. 103. See also Eng. News, July 21, 1892.

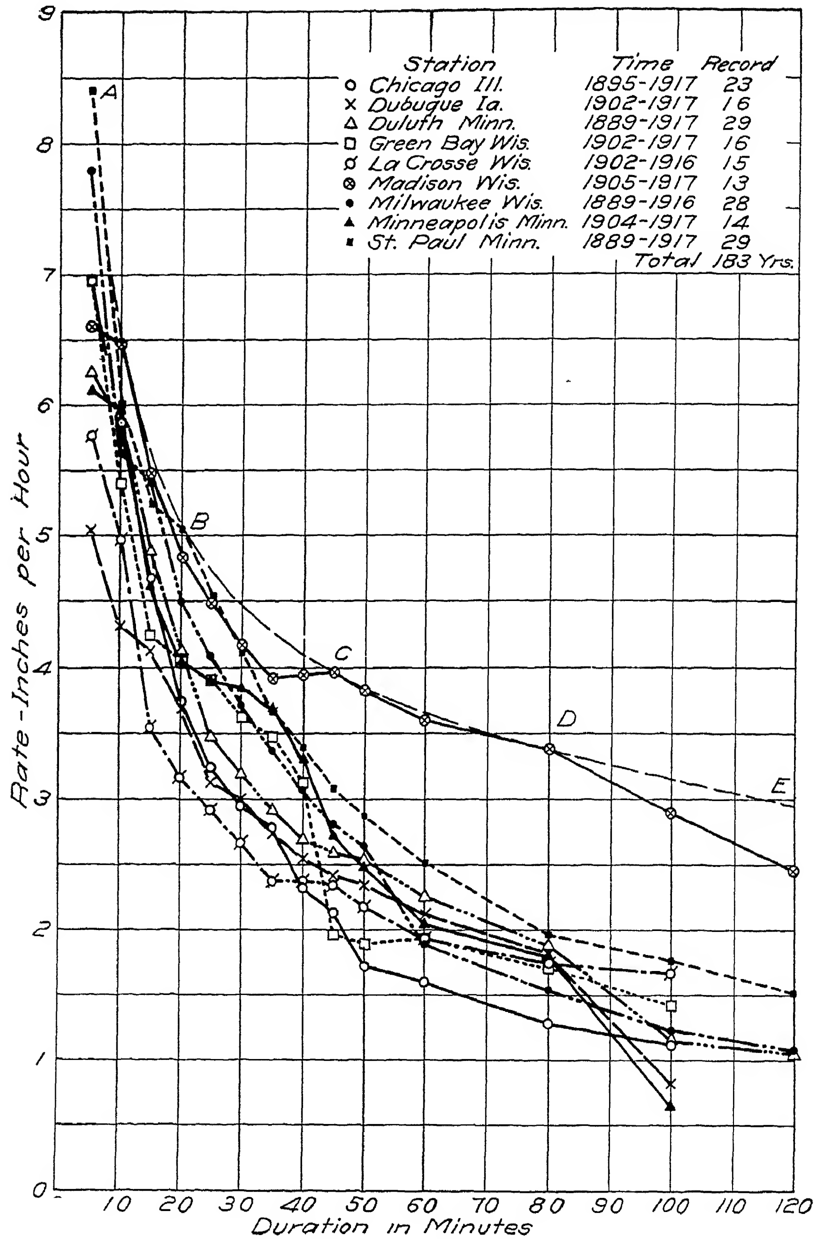

FIG. 142.—Maximum Rates of Rainfall for Wisconsin Conditions (see page 259).

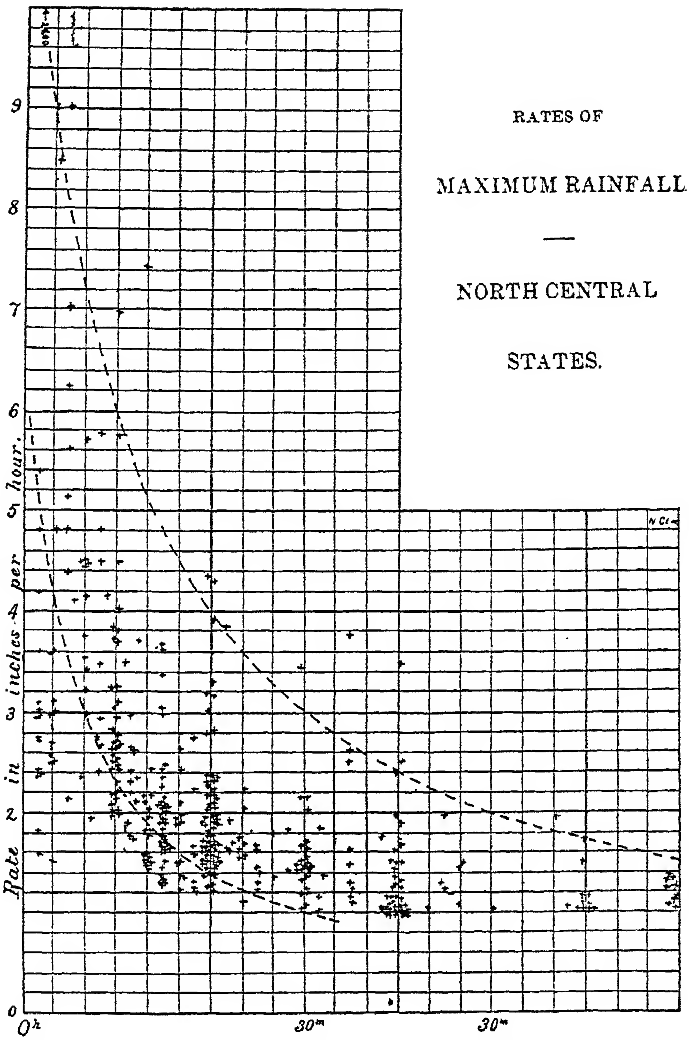

FIG. 143.—Talbot's Study of Maximum Rainfall Intensities of Short Duration (see page 259).

investigations are given by the following formulas in which i is the rate of precipitation in inches per hour, and t is the duration of time expressed in minutes: In this tabulation are also given the formulas of Prof. Talbot, reduced to similar units for comparison.

TABLE 28.

Formulas for Maximum Rainfall.

	Formula	Author	Remarks
1.	$i = \frac{105}{t + 15}$	A. N. Talbot[10]	Ordinary maximum
2.	$i = \frac{180}{t + 30}$	A. N. Talbot	Maximum occurring once in about 15 years
3.	$i = \frac{360}{t + 30}$	A. N. Talbot	Maximum exceeded 2 or 3 times per century
4.	$i = \sqrt{\frac{54}{t}}$	E. W. Clarke[11]	To be expected each year
5.	$i = \sqrt{\frac{162}{t}}$	E. W. Clarke	Exceeded once in 8 years
6.	$i = \sqrt{\frac{324}{t}}$	E. W. Clarke	Exceeded once in 15 years
7.	$i = \sqrt{\frac{120}{20 + t}}$	Kuichling[12]	
8.	$i = \frac{38.64}{t^{0.687}}$	Sherman[12] (Chestnut Hill).	Maximum
9.	$i = \frac{25.12}{t^{0.687}}$	Sherman	Ordinary
10.	$i = \frac{12}{t^{0.5}}$	C. E. Gregory..............	Ordinary severe storm
11.	$i = \frac{6}{t^{0.5}}$	C. E. Gregory..............	Winter storms
12.	$i = \frac{32}{t^{0.8}}$	C. E. Gregory..............	Maximum

[10] Rates of Maximum Rainfall. A. N. Talbot. The Technograph, 1891–2, page 103. Also, Rainfall and Runoff in Relation to Sewerage Problems. W. C. Parmley, Jour. Assoc. Eng. Soc., 1898.

[11] Storm Flows from City Areas, and Their Calculation. E. W. Clark. Eng. News, Vol. 48, p. 386.

[12] Rainfall and Runoff in Storm Water Sewers. C. E. Gregory. Trans. Soc. C. E., Vol. 58, p. 458. Also, Maximum Rates of Rainfall at Boston. C. E. Sherman. Trans. Am. Soc. C. E., Vol. 54, p. 173.

Figure 144, page 264, shows a platting of a number of formulas together with some curves for maximum rainfall rates which have been devised by various writers but which have not been reduced to a mathematical expression.

The variation in the formulas and curves is due to the fact that they were derived from records of different localities and in some cases for quite different frequencies. In this figure, Curve 8 was constructed from the combined records of excessive rainfalls in the cities of Boston, Providence, New York, Philadelphia and Washington and represents the observations for an aggregate of about seventy years, and was the curve adopted by the engineers who made the report on the sewerage of the District of Columbia in 1890.

An examination of the various curves shown in Fig. 144 will make it manifest that the application of any single formula to the determination of probable locál rainfall intensity is liable to lead to very erroneous results, unless it is first determined whether or not the formula actually applies to the particular condition of the locality. In all cases where the problem to be solved is of importance, an independent investigation should be made, or the origin and basis of the formula or intensity curve considered should be ascertained and its real application to the particular locality determined.

128. **Rainfall for Longer Periods.**—Professor F. E. Turneaure has investigated the local rates of rainfalls that have occurred during longer periods and within certain general geographical boundaries, and has embodied the maximum results of his study in Fig. 145. Concerning the investigation on which this diagram was based, Turneaure says:

"The records cover the period from 1871 to 1906, and all rainfalls are represented which exceeded in amount five inches in twenty-four hours, and, from 1894 to 1896, all those which equaled or exceeded two inches in one hour. As far as possible, the same storm is represented but once for any one state, although records may have been received from several stations; and furthermore each storm is counted as a one-day storm or a two-day storm, but not both. A one-day storm is one in which all the rain falls in a meteorological day, that is, from 8 P. M. to 8 P. M., and in a two-day storm, all the rain falls within two such days. A one-day storm may therefore have fallen in a few hours, and likewise a two-day storm, so that the figures given do not necessarily represent the maximum rates. However, by taking the maximum from among a great many records the figures thus found

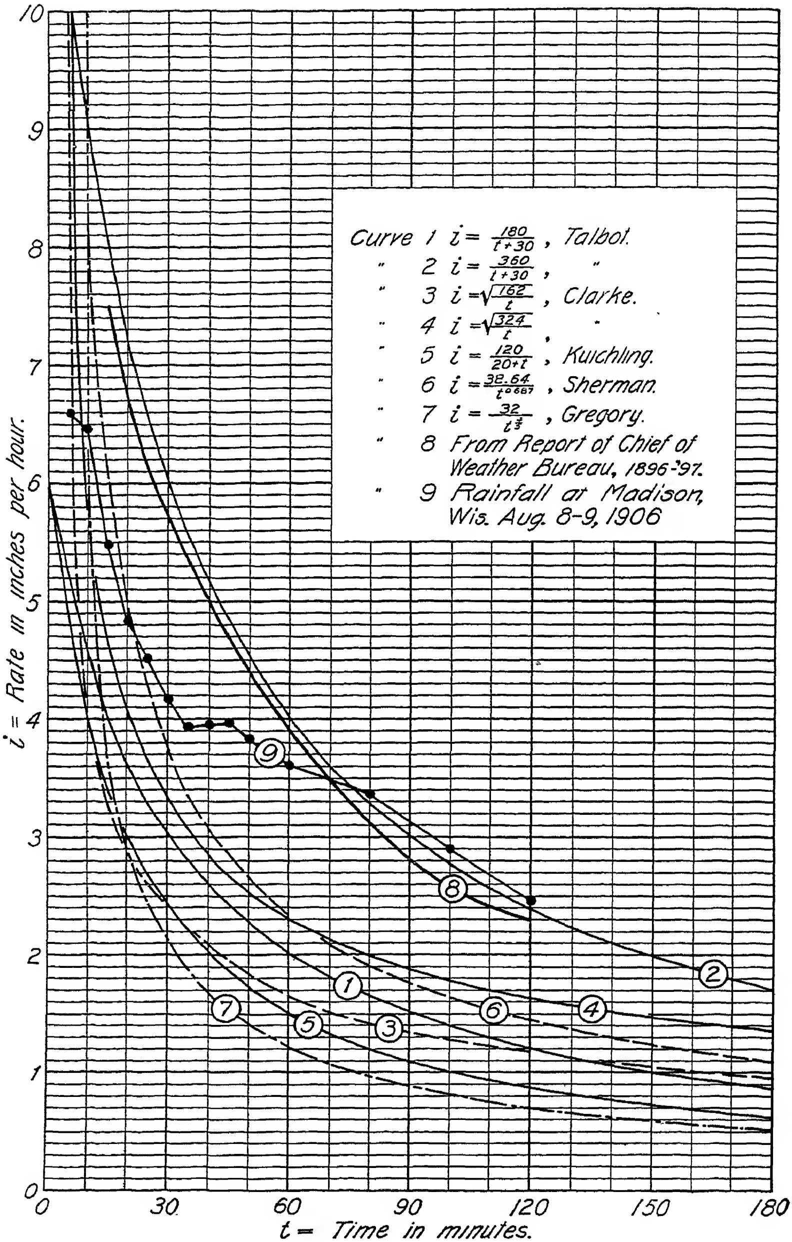

FIG. 144.—Intensity Curves for Storms of Short Duration (see page 263).

for the one and two-day storms will approximate the maximum for twenty-four and forty-eight hours. The one-hour rates are well determined. The number of times a rainfall has exceeded the given amounts is an indication of the frequency of heavy storms and also to some extent, of the reasonableness and reliability of the maximum figure. Those states having the highest maximum rates are those where heavy rainfalls are the most frequent.

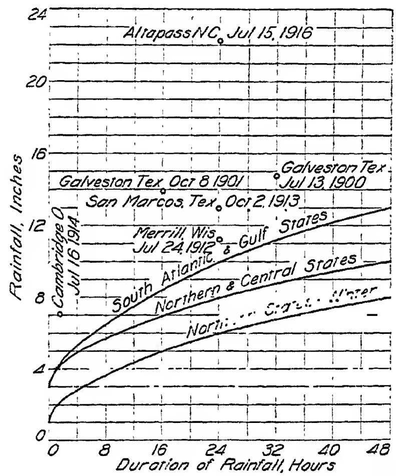

FIG. 145.—Turneaure's Curve of Local Rainfall Intensities (see page 263).

"The curve for the Northern and Central States is somewhat exceeded in a few states, but for most of them it represents rainfalls but little greater than those which have already been observed and which may occur again at any time. The curve for the South Atlantic and Gulf States represents the maximum recorded rainfalls for all the states of this group except Louisiana, for which the records far exceed those of any other state." [13]

To the original figure have been added the rainfall at Cambridge, Ohio, July 16, 1914, and at Altapass, North Carolina, for the maximum twenty-four hours of July 15–16, 1916, and a few other records of extreme rainfalls. As noted from the above quotation, the curves were not drawn to show extreme maximums but rather the probable maxi-

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13 Public Water Supplies. Turneaure and Russell. 2d Ed., p. 49 et seq. See also Table 7 for detailed study on which diagrams were based.

mums for perhaps a twenty-five year period. The added data show that to include extreme intensities, the curves would all probably have to be raised considerably and that even for a twenty-five year period they might have to be altered somewhat in the light of the twenty years of observations which have elapsed since the end of the period on which the curves are based.

129. **Intensity Over Large Areas.**—The local intensity of rainfall which has been previously considered is that determined from single stations or groups of stations and is therefore applicable only to limited areas. Such intense rains never extend over large areas, and the estimates based on such observations cannot be applied to any considerable drainage areas. It is to be noted, however, that it is by no means certain that the maximum intensity recorded by a given gage in a certain area represents the maximum intensity of rainfall that has occurred on that area, and indeed it is probable that the records in practically all cases are actually below the maximum that has occurred as the gage area is such a small part of the area which any storm covers. This fact somewhat offsets the error in the application of the data to areas of considerably greater size, which would not be warranted otherwise.

In the consideration of the flood flows of streams and the maximum discharge of considerable drainage areas, the factors of both intensities and area become important, and the engineer must again have recourse to the records of the Weather Bureau.

In the great storms of March 24–27, 1913, which were the main cause of the flood of the same dates, the ground over most of the regions where floods occurred had previously been saturated by the storm of March 20–23, 1913, which has been illustrated in Fig. 31, page 70. This storm was almost immediately followed by the storm of March 24–27 although there was a sufficient cessation of rain to make the two storms entirely distinct. The extent of the storm of March 24–27 for each of the days included is shown by Fig. 146, page 267, and its distribution of intensity over the area particularly affected by the floods is shown in Fig. 147, page 268. By measuring the areas surrounded by the various isohyetal lines, the distribution of the rainfall of this storm for different intensities can be approximately determined; and by a similar measurement of similar maps drawn to show the distribution of the maximum rainfall for one, two and three days, similar data can be approximately determined for such periods. Figure 148, page 268, shows curves for the distribution of intensity

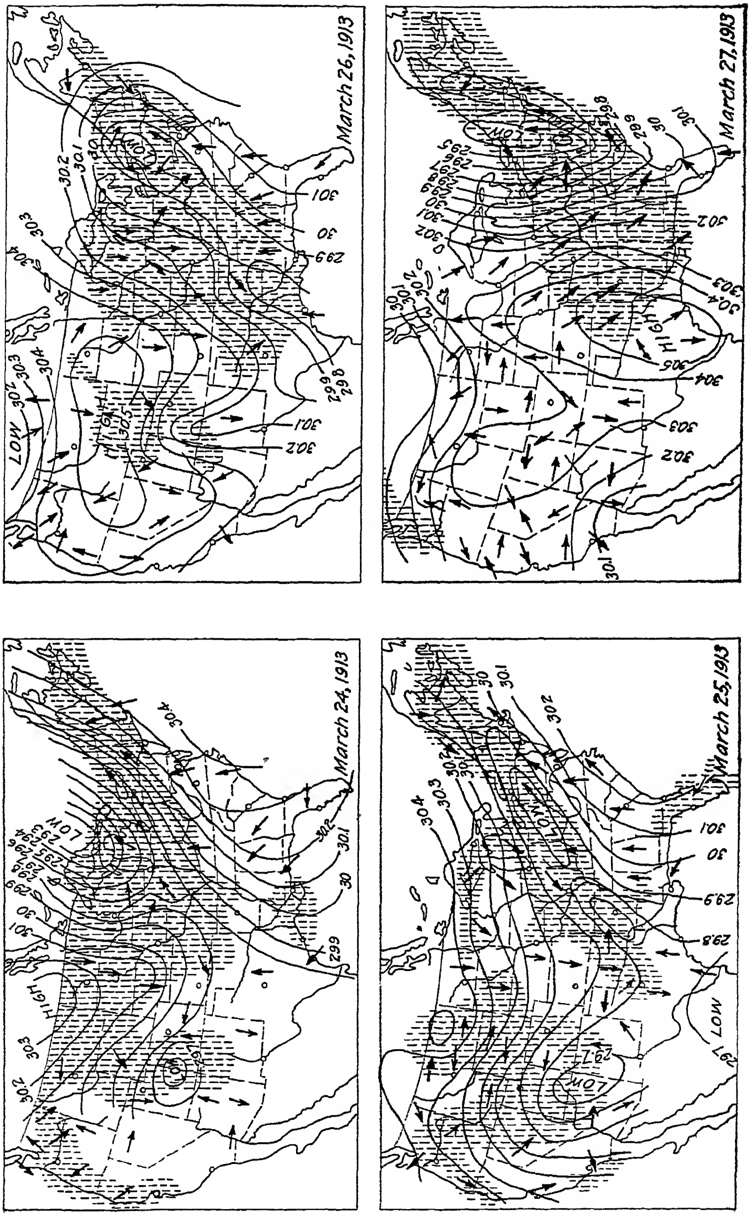

FIG. 146.—Extent of Storm of March 24–27, 1913 (see page 266).

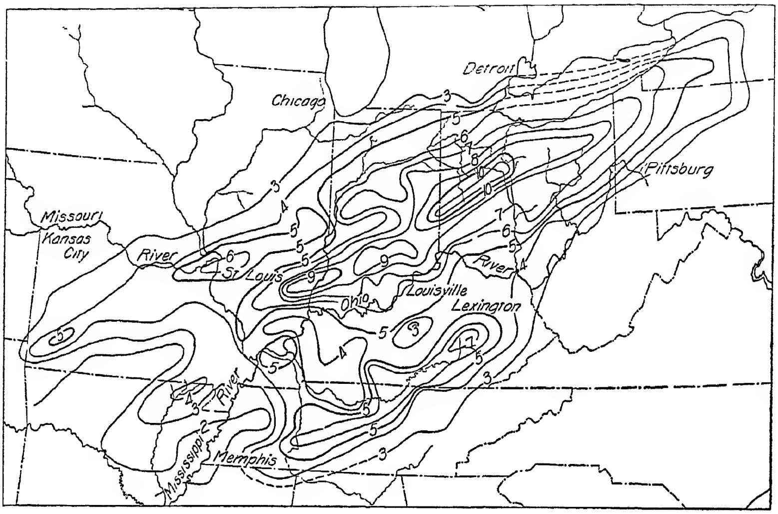

FIG. 147.—Depth of Rainfall, March 24–27, 1913 (see page 266).

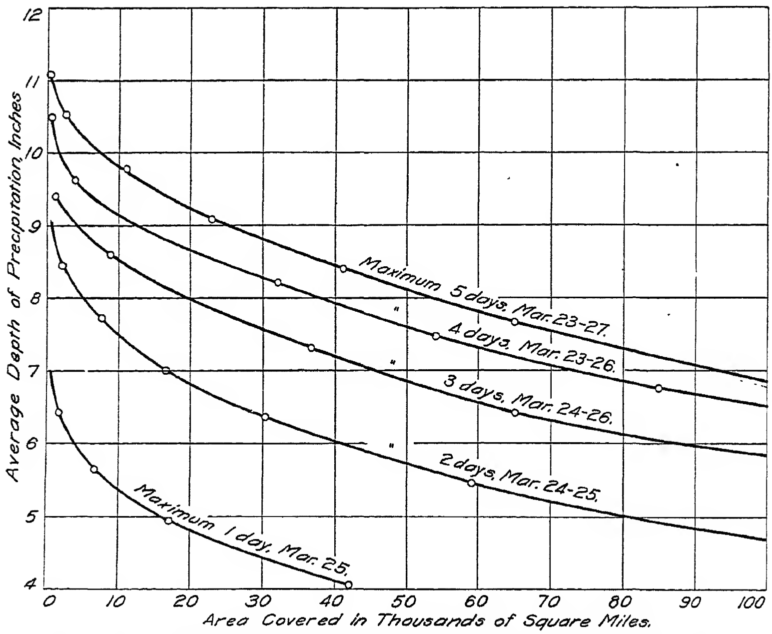

FIG. 148.—Rainfall Intensity for One to Five Days (see page 266).

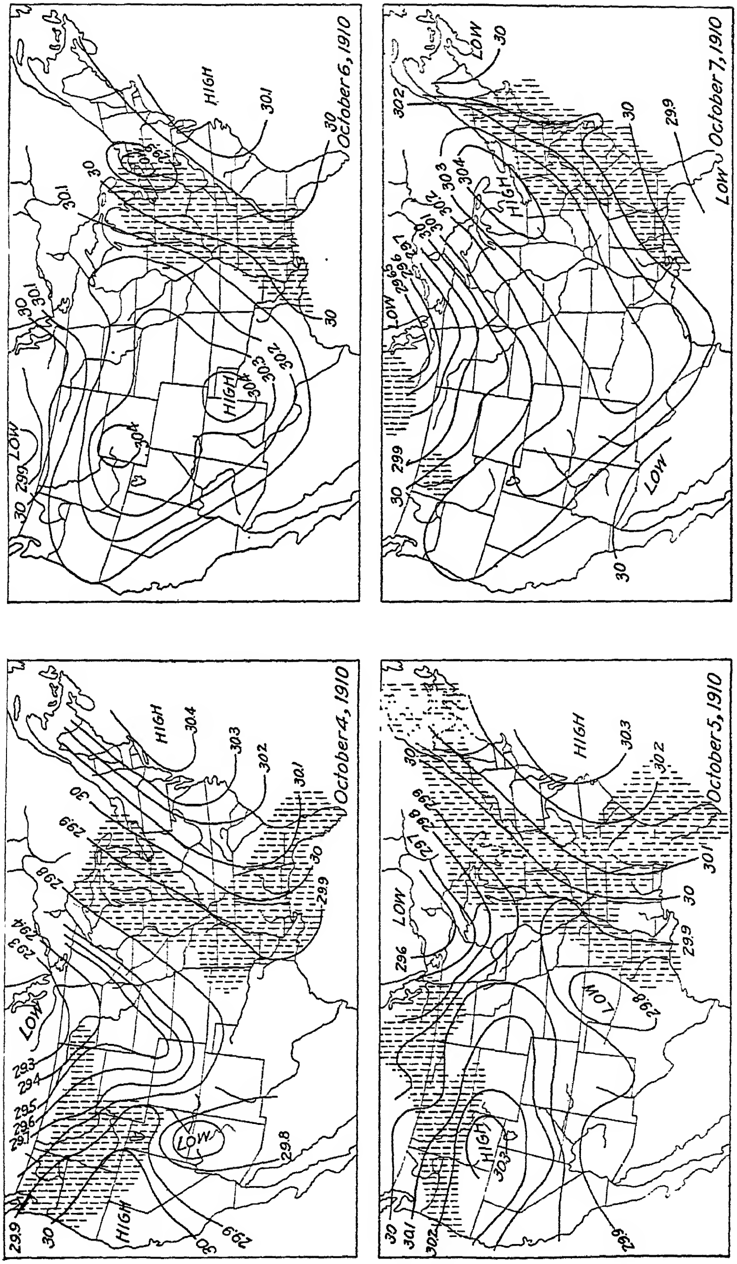

Fig. 149.—Extent of Storm of October 4–7, 1910 (see page 270).

of this storm for periods of one, two, three, four and five days.[14] In the investigation of the problem of the maximum storms which might possibly visit this area, it was soon ascertained that a storm on essentially the same path had occurred in October, 1910, but that the most intense rainfall had occurred westerly from the center of the area of intense precipitation of the storm of March, 1913.

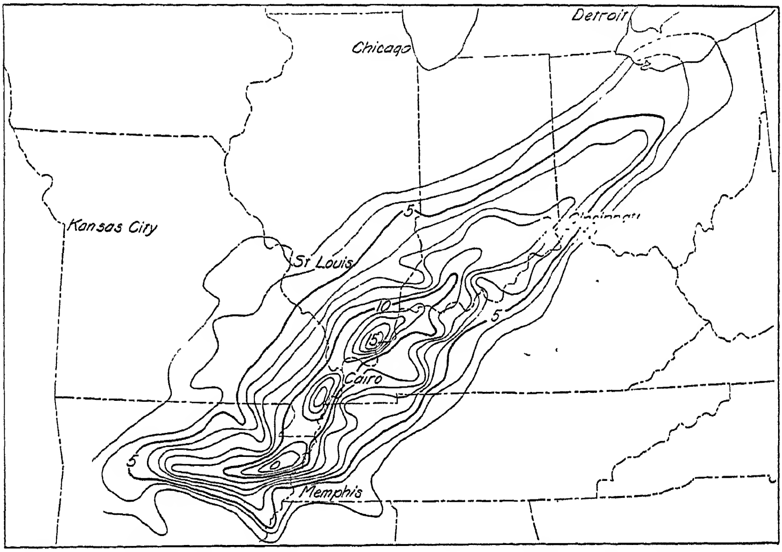

FIG. 150.—Isohyetal Lines for Storm of October 4–7, 1910.

The path and geographical extent of the storm of October, 1910, is shown in Fig. 149, page 269, and the isohyetal lines are shown in Fig. 150.

130. **Excessive Rainfall of the Eastern United States.**—After the great flood of March, 1913, an investigation of both rainfall and flood records was undertaken by the Miami Conservancy District in order to determine whether the flood that had just occurred might be regarded as the maximum that might ever be expected or whether the flood protective work should be designed for a flood of greater magnitude. This work, which was undertaken by the Morgan Engineering Company under the direction of Mr. A. E. Morgan, Chief Engineer, is believed to be the most complete and thorough investigation of the problem of the intensity of rainfall over extended areas that has ever

[14] From data furnished by A. E. Morgan, Chief Engineer Miami Conservancy District.

been attempted. While the research was undertaken with special regard to Ohio and the adjacent country, it covered quite thoroughly the eastern half of the United States and will furnish a basis for reliable estimates over this entire area. As a basis for this study, the rainfall records were abstracted for all storms in the United States east of the 103° of longitude, including all rainfalls that equaled or exceeded the following limits:

For stations where normal annual rainfall exceeded twenty inches, all storms where the total rainfall for a single day equaled 10 per cent or the total rainfall for the entire storm equalled 15 per cent of the normal annual rainfall.

For stations where normal annual rainfall was below twenty inches, all storms of one inch in twenty-four hours or four inches for the total storm.

The investigation included some 3,000 stations. Some of the most valuable results of these studies relative to local rainfalls are embodied in six maps showing the maximum rainfalls in each of the quadrangles in one to six days.[15] These maps have been summarized in Figs. 151 and 152, pages 272 and 273. In Fig. 151 the maximum rainfalls for 1, 2 and 3 days are shown in each quadrangle, and in Fig. 152 the maximum rainfalls for 4, 5 and 6 days are also shown. These maps include only data available to Dec. 31, 1914, and for stations having rainfall records for five years or more. These investigations include 2641 storms. Of these 1,236 were found to be storms registered at only single stations and therefore of no great geographical extent. Nine hundred and ninety-six storms were recorded at from two to five stations, and 409 storms were recorded at more than six stations. For the purpose of the investigation, only storms that covered 500 square miles or more and that had a total precipitation of at least 20 per cent of the normal annual rainfall were studied in detail. Of seventy-eight such storms, the twenty-seven largest were chosen for final consideration. The geographical location of these storms as shown by the limiting isohyetal lines of five inches of rainfall is given in Fig. 153, page 274.

131. The Application of Data.—In considering the rainfall data available from areas widely separated geographically, and consequently greatly differing in climatological conditions, it is important to determine what data may be regarded as applicable to local conditions.

It has already been pointed out that local rainfall is induced by cer-

15 Storm Rainfall of Eastern United States, by the Engineering Staff of the District. Technical Reports, Part V. The Miami Conservancy District, Dayton, Ohio, 1917.

tain conditions among which the most important are the directions, paths and intensities of the storms to which the locality is subjected and its situation relative to the sources of moisture from which the rainfall must be derived. While storms of great intensity occur far

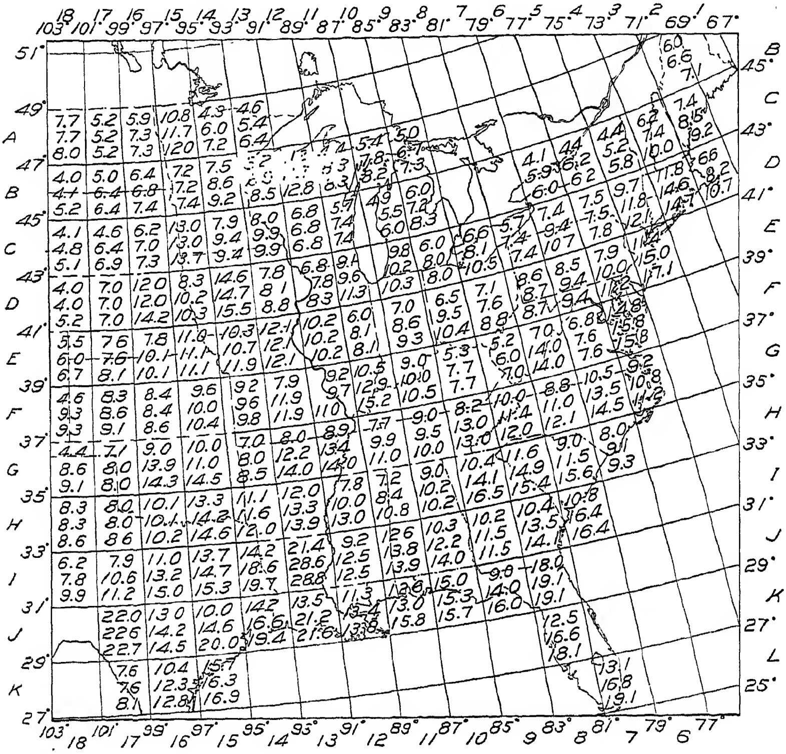

Fig. 151.—Maximum Depths of One, Two and Three Day Rainfalls.

from the location of areas of maximum evaporation, it is evident that such distances limit to a considerable extent, the frequency of occurrence, the duration of high intensities the extent of area over which such intensities may occur, and the maximum intensities to which such localities may be subject. While the storms of July, 1914, in Ohio (see Sec. 121) and of July, 1912, in Wisconsin (see Sec. 123) are equal to many similar storms which have occurred in the Gulf and South Atlantic States, it is believed that such storms are approximating a maximum, for those localities, and that no such storms as those which occurred in the Carolinas in July, 1916, in Porto Rico on August 5–9, 1889, or at Mont-

erey, Mexico on August 25–29, 1909, are physically possible in Wisconsin, Ohio or other regions similarly located.

It is also important to note that the greatest local or general storms are likely to occur during seasons when evaporation and con-

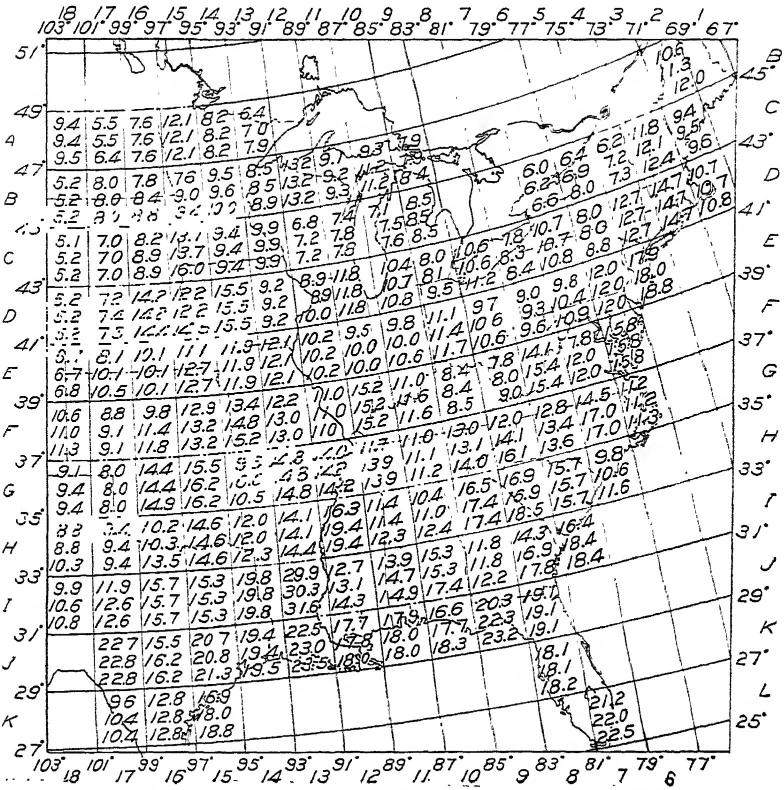

Fig. 152.—Maximum Depths of Four, Five and Six Day Rainfalls.

sequently atmospheric moisture is at a maximum, that such conditions appear essential to their occurrence, and that in consequence it is improbable that even such excessive storms as are known to occur can occur during cold periods, especially in the north when the ground is covered by a deposit of snow.

While a storm similar in intensities to the great storm of October, 1910, must be anticipated as a future possibility at other localities in the country adjacent to its path, it is unlikely that such a storm will occur during the early spring under conditions of materially lower temperature. It is not therefore to be anticipated for any given locality

that with the lapse of time, storms are bound to occur which will be equal to any other storms which may have occurred in any other locality. For each particular locality there are undoubtedly limits which it is physically impossible that rainfall can exceed in intensity, duration and extent. What those limits may be cannot be determined with

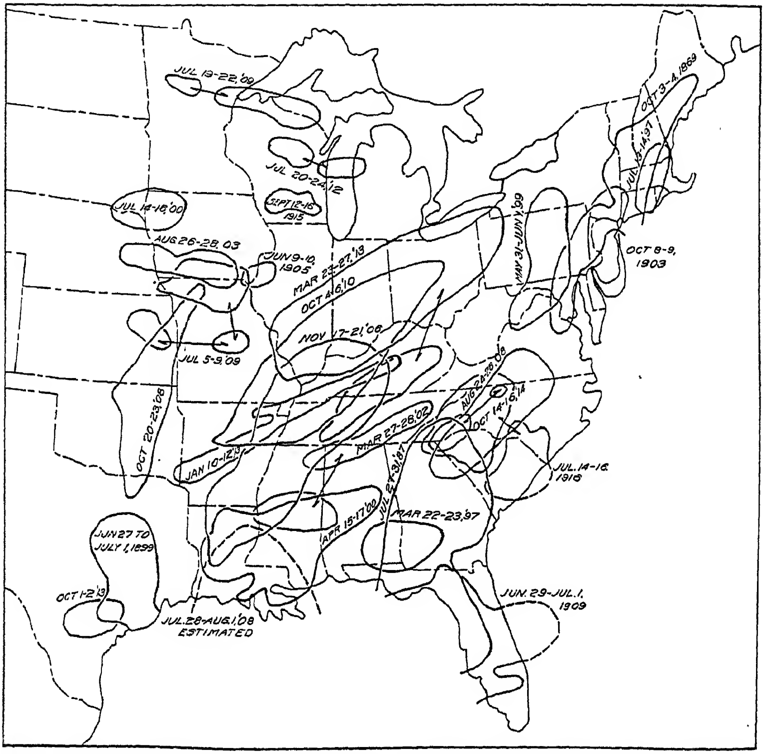

FIG. 153.—Limit of 5-inch Isohyetals of Great Storms of Eastern United States.

any great degree of exactness on account of the short time for which rainfall records are available, but the observations of the flow of streams in other countries for many centuries, bear out the conclusion that such limits do exist and that they can be approximately determined.

When such flood records are available for hundreds of years, the flood heights of the several greatest floods agree within a few feet of each other, and in such long time records no one flood is found to greatly exceed other extreme floods. The greatest flood that occurs once in a thousand years does not greatly exceed the maximum flood of one hundred or even of fifty years. It is reasonable to assume that the

great rainfalls, which are the principal underlying cause of the floods, will not in the lapse of centuries vary to a much greater degree than the floods they produce.

132. **Frequency of Storms of Various Magnitudes.**—In the studies of maximum rainfall undertaken by the Morgan Engineering Company for the Miami Conservancy District, the country east of the 103 meridian was divided into districts on the odd degrees, thus giving 133 two-degree quadrangles. (See Figs. 151 and 152, pages 272 and 273.) To determine the frequency of storms of various magnitudes as well as the maximum storm which might be expected to occur within a given period of time in each quadrangle,[16] the years of record for each of the several stations within each quadrangle were totaled, as were also the occurrence of storms of a given intensity. By dividing the total year of experience in the quadrangle by the number of storms of the given intensity, the time interval was estimated for that particular storm intensity. By repeating this process for storms of various intensities, estimates were made for which frequency curves for each quadrangle were constructed. The quadrangle which includes the Maimi River is shown on Fig. 154, page 276, and the frequency curves for this quadrangle, based on estimates made as above described, are also shown in the same figure. From these curves the frequency of the maximum storm intensity for one or more days within the experience of the Miami quadrangle can be estimated, and the probabilities of greater storms within terms of years beyond the experience of the area can be approximated by their extension. It will be noted that the general form of the curves is similar to and vertified by the local intensity curves previously shown in Fig. 134, page 249.

In order to compute the intensity of a storm that will probably occur once on an average of 50 or 100 years, the sum of the record years of all stations in each quadrangle was divided by the number of years in the period considered. For example: if a total of 360 storm years were on record in a given quadrangle, the average maximum storm for a 50 year period would be the average of the seven (7.2) maximum storms experienced, and for a 100 year period the average of the four (3.6) maximum storms experienced. For this purpose no station with a record of less than 10 years was considered.

The results of these studies are embodied in some 24 "Isopluvial" charts for 15-year, 25 year, 50 year and 100 year periods, and for 1, 2, 3, 4, 5 and 6 days rainfall for each period, all constructed on the above

[16] Eng. News, Vol. 77, p. 15.

principle.[17] Maps so constructed are perhaps reasonably indicative of conditions which may be expected to obtain. They represent an attempt to analyze a most complicated subject by using such data as are now

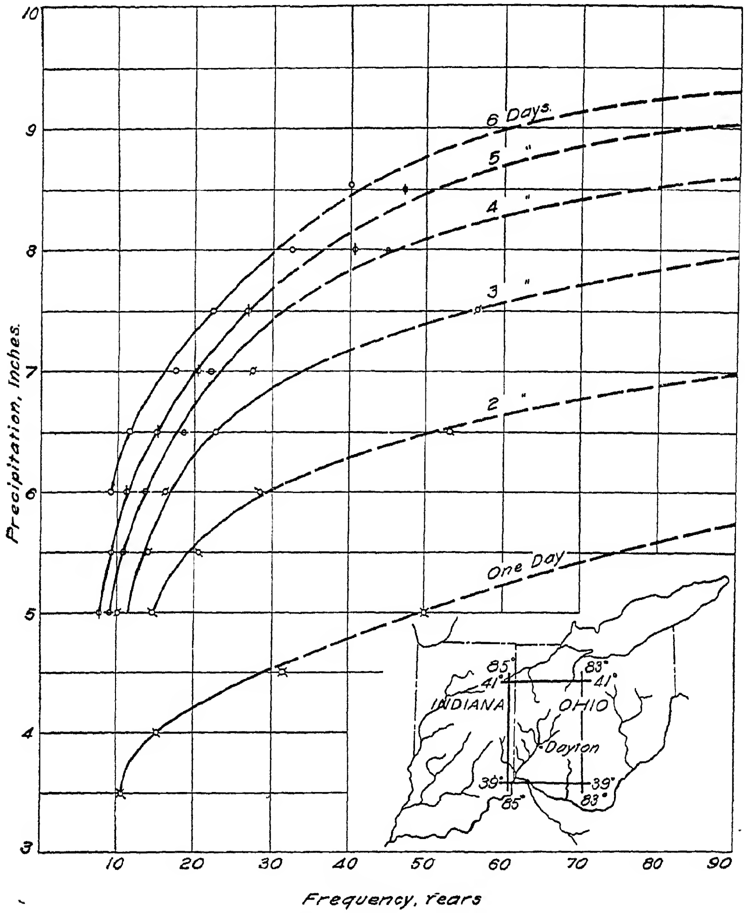

FIG. 154.—Intensity Studies for Miami Quadrangle[16] (see page 275).

available but which are admittedly insufficient for drawing definite conclusions.

The reliability of this method of investigation for determining the fre-

[17] Storm Rainfall of Eastern United States. Technical Reports, part V, Miami Conservancy District, 1917.

quency of maximum rainfall occurrences depends at least partially upon the actual occurrence of the maximum extreme conditions within the experience of some of the stations within the quadangle or district considered. If the occurrence of rainfalls of great magnitude is of a periodic character for correct results the period of maximum intensities must be included in the record, and if occasional exceptional conditions will occur at very rare intervals, they will not be discovered unless very long records are available.

This method while an interesting basis of investigation, cannot be regarded as strictly correct for if correct it should be possible to obtain 300 years of experience from 300 one-year observations at 300 separate stations within a single quadrangle. It is evident that as all such limited areas must be subject to similar meteorologic conditions, an exceedingly dry or an exceedingly wet period would affect all of the stations and thus give erroneous conclusions. It is evident that the occurrances at any station in a district having similar meterological conditions may be taken as a fair criterion of what may occur at other stations in that district; but the extreme occurrences at any one station will not fairly represent the extreme which may occur at any one station during a period equal to the sum of all the periods for which observations have been taken at all the stations in the district.

133. **Tlme-Area-Depth Curves for Major Storms.**—In the investigations of the Miami Conservancy District,[18] the study of major storms included among others the nine major storms listed in Table 29.

TABLE 29.

Major Storms Considered by the Engineers of the Miama Conservancy District as Applicable Thereto.

Index	Date		Center of Storms
a	May 31–June 1,	1889	Pennsylvania
b	July14–16,	1900	Iowa
c	Aug. 26–28,	1903	Iowa
d	June 9–10,	1905	Iowa
e	July 5–8,	1909	Kansas
f	July 19–22,	1909	Michigan
g	Oct. 4–6,	1910	Southern Illinois
h	March 23–27,	1913	Ohio
i	August 17–20,	1915	Arkansas

The time-area-depth curves of these storms for one, two and three day periods are shown in Figs. 155, 156, and 157, pages 278 and 279.

It should be noted that all of these storms, with the exception of that which actually produced the great flood in the Miami Valley, occurred

[18] Report of Chief Engineer, Miami Conservancy District, Vol. I, p. 87 et seq.

late in the season and it is improbable that storms equal to the three maximum will ever occur in the Miami Valley early in the season with frozen or snow covered ground.

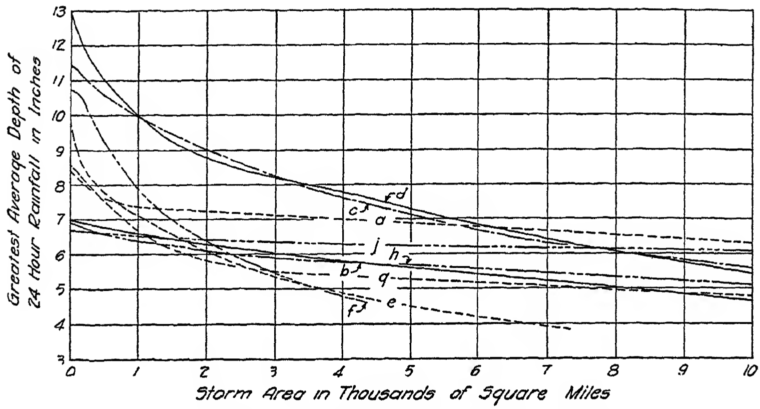

FIG. 155.—Time-Area-Depth Curve for 24-Hour Storm.

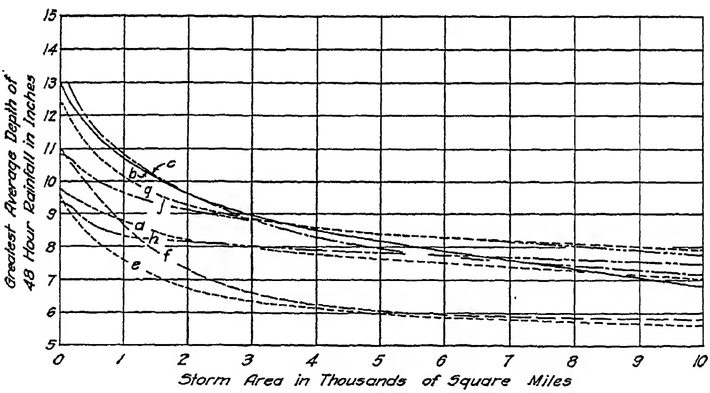

FIG. 156.—Time-Area-Depth Curve for 48-Hour Storm.

Nevertheless the uncertainties involved warrant the use of adequate factors of safety in all designs involving the safety of life and property.

134. **The Study of Extreme Conditions of Rainfall.**—In estimating extreme conditions additional light can be obtained by examining the extremes at other stations within a district having similar meteorologic conditions and basing maximum and minimum estimates on limits

fixed by similar occurrences within the district; but the frequency with which such events are likely to recur can at best be but roughly estimated. The extreme conditions of the one day rainfall for quadrangle B–12 in northern Wisconsin, shown in Fig. 151, are largely fortuitous and are scarcely liable to recur at the same locality in perhaps the next one hundred years or more but are liable to occur at any time at some other point within Wisconsin or in adjacent states. In the same way the extreme intensities of the storm of June, 1889, at Alexandria, Louisiana, shown in quadrangle L–13 will scarcely be expected to obtain

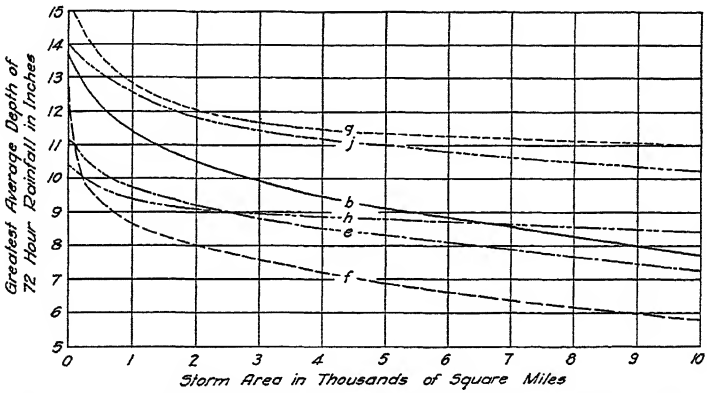

FIG. 157.—Time-Area-Depth Curve for 72-Hour Storm (see page 277).

again at this locality for many years; but it seems quite probable that a similar storm may occur at any time within the Southern States as did the storm of July, 1916, in the Carolinas which, had it occurred at the time of the construction of these maps, would have materially modified the intensities shown for the quadrangle G–8. The maximum departure from the mean annual rainfall at Madison is + 21.3″ and —18.14″. It seems quite possible that any station in Wisconsin may experience departures of equal magnitude, but the combination of all the station experience in the State would not give the frequency of occurrences that the sum of those observations represent, and would lead to a false idea of the meaning of the data.

The extraordinary rainfall of August 8–9, 1906, at Madison, Wisconsin, was found to be the storm of maximum intensity for periods of from 30 to 120 minutes for stations in and adjoining the State of Wisconsin, as shown in Fig. 142, page 260. It is evident that the frequency at which such a storm must be expected to occur in any locality in Wis-

consin cannot be definitely or even approximately evaluated with the limited records available. The combined time of record shown in Fig. 142 is 183 years, but in comparison with the estimated length of the maximum experience at St. Paul (Section 125), this would be too low an estimate of frequency for the Madison storm.

The necessity of long time records to cover extreme variations in annual rainfall is illustrated by the curve of progressive means for Southeastern New England (see Fig. 117, p. 211). This curve is below the mean for 26 years from 1833 to 1858 inclusive, and there are 52 years between its minimum in 1837 and its maximum in 1889. It is probable that frequency determination and intensity-duration-depth maxima, even when considered for extended areas, may require a similar or even a greater time for their full appreciation. It seems probable therefore that the average length of record of the various stations for which observations are available especially in many parts of the area covered by Figs. 151 and 152, is not sufficient to fully cover the long time probabilities, and that in some cases the occurrence of unusual and rare storms, on account of the time limitations of the data available, unduly accentuate the occurrence of intensities in certain districts and underrate the probabilities of similar occurrence in other districts.

135. **General Conclusions.**—It is important that all should recognize our unfortunate but necessary ignorance of the frequency with which such extraordinary events obtain, and that we are entirely unable to formulate any exact rules for such occurrences. In many cases the controlling element of cost will not permit works to be designed to care for such unusual conditions, and in cases where property loss alone is to be considered and where no loss of life is involved, the extreme conditions must be ignored in the design with the understanding that occasional loss is more desirable than unwarranted expense. Deductions that can be drawn from extended studies on lines similar to those above discussed, especially when the studies apply to the older parts of the country where considerable data are available, are believed to furnish an adequate basis for engineering design. Such uncertainties as remain must be covered by adequate factors of safety.

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CHAPTER XII

RAINFALL AND ALTITUDE

136. Importance of Subject.—A brief discussion of the relations of altitude and precipitation has been presented in Sec. 87, but the importance of the subject is such that a more detailed consideration seems desirable. The fact that in many cases precipitation increases with altitude is well known, but the further fact that this condition is not universal and that such increase, if any, is sometimes obscured or even reversed by the influence of the geographical location with reference to sources of moisture and storm paths and by topographical relations is not always understood or appreciated. Attempts must occasionally be made to estimate the quantity of a water supply which may be expected from a mountain drainage area on the basis of the known rainfall at valley stations, for which alone data are usually available. In some cases the data are sufficiently complete and the conditions sufficiently well known to warrant the assumption that the mountain rainfall will exceed the valley rainfall, and a fairly positive estimate is possible of the probable effect of altitude on the average rainfall conditions on the drainage area which is under investigation. Such estimates, however, are sometimes made on insufficient data or on a basis that is found to obtain at other localities where conditions may be widely different. Unless estimates are made with great care and based on sufficient pertinent data, they are likely to be seriously in error and to be followed by disastrous results. Sometimes the desire for a sufficient water supply rather than a careful consideration of the physical conditions modifies the estimates, and works that are constructed on such unfound assumptions must usually result in failures more or less complete.

The study of such problems in almost every case is greatly complicated by the lack of rainfall stations in the mountains. Comparatively few such stations exist, and information covering many areas is entirely lacking. In other cases, where a few such stations are established, the data are more or less incomplete and misleading for the detailed distribution of rainfall in the mountains is more uncertain than in the country having more uniform topography on account of the fact that the irregular topography of the mountains greatly affects the distribution of the quantity of precipitation and the variations from point to point in adjacent territory are very irregular.

Several attempts have been made to express the relations of altitude and rainfall by rules or formulas (see Sec. 143), and however commendable such work may be when limited in application to local conditions, such rules are exceedingly misleading when an attempt is made by the uninformed to apply them to general use. For these reasons a study of the subject in some detail seems desirable and a still more detailed study of local conditions is essential when a working estimate is to be made for any important purpose.

137. **General Considerations.**—The greatest annual rainfall usually occurs where moist winds are forced to rise in passing over mountains, causing dynamic cooling and consequent precipitation. Such conditions more especially obtain where mountains rise abruptly from the sea and are located in general at right angles to prevailing storm movements, as is the case on the North Pacific Coast of North America (see Fig. 109, page 201), the west coast of Scotland, Norway, Dalmatia, India, Japan and numerous other similar locations. Similar conditions also obtain on mountains at some distances inland where extreme rainfall conditions are occasioned by winds of exceptional intensity such as the hurricane winds that produce the heavy precipitation on the Southern Appalachians in North Carolina (see Fig. 96, page 175), and the monsoon winds (see Fig. 24, page 61) that produce the excessive precipitation on the Himalayas of Northern India. These conditions not only increase the rainfall on the windward side of the mountains and to some extent on the low lands to windward, but also comparatively decrease the rainfall to some distance to the leeward of the mountains. As the winds pass over the divide, their absolute humidity having been decreased by the induced rainfall, they are compressed in their flow down the mountain, and in consequence become dry winds. In some cases after such reduction in rainfall has occurred, heavy precipitation again results from higher ranges of mountains farther inland. This is shown by the conditions in California, illustrated by Fig. 91, page 170. The low coast range which rises abruptly from the Pacific Coast induces an average annual precipitation of about 60 inches, producing also a comparative reduction of the annual rainfall to 40 inches and less on the contiguous inner ranges and to 20 inches and less on the interior valley. In ascending the Sierra range the rainfall again increases to an average of 40 inches and over, decreasing again in the mountains and valleys beyond. In India the South West monsoons (see Fig. 24, page 61) first encounter the Western Ghauts (elevation 5,000 to 6,000 feet) which induce a rainfall of from 80 to 160 inches. Beyond these mountains there is a reduction in pre-

cipitation to about 20 inches which again gradually increases to 40 inches or more in the interior, reaching the heaviest precipitation encountered any where in the world at certain stations in the Himalayas (see Table 27, page 248). The rainfall in the Himalayas is said to decrease above 5,000 feet, to fall to about 30 inches near their top and to 10 inches and less in the interior plains of Tibet.

In Norway the annual rainfall is 88.70 inches at Bergen, 145.15 inches at Seathwart in the mountains, and 189.43 inches at Sty-head pass (elev. 1,600 feet), while at Christiania on the lee of the mountains it is 21.18 inches.

The mountains having the greatest rainfall in Germany are the Wasgenwald and the Schwarzwald. The following table shows how the rainfall increases with the altitude, taken in the Thur Valley of the Southern Vogesen Mountains in the year 1880.

TABLE 30.

Rainfall in the Vogesen Mountains.

Station	Altitude Feet	Rainfall Inches
Sennheim	900	32.28
Thann	1,100	38.19
Weiler	1,260	55.90
St. Amarin	1,320	59.06
Wesserling	1,400	64.18
Odern	1,510	75.98
Wildenstein	1,870	99.21

In similar manner, Osterode in the Harz Mountains has 31.30 inches of rainfall, while only seven miles away at Klausthal, 1,160 feet high, on the rainy side of the mountains, the rainfall is 58.70 inches.

In many cases diagrams platted to show the relation of altitude to rainfall for certain valleys or topographical districts (see Fig. 158, page 286) indicate a marked increase in rainfall with altitude, and with selected stations the relation is frequently so definite as to give confidence in the possibility of the establishment of dependable rules for such relations as applied to local conditions. As more stations are added to the diagram, considerable exceptions are found to exist and any rule so established is seen to be liable to serious error unless topographical relations are considered, and even such considerations will with our present knowledge be inadequate to explain all of the discrepancies.

This diagram shows an interesting feature in the continually diminishing rates of the increase of rainfall with altitude as the river valleys considered become more and more shut off from the ocean. The

rate of increase of rainfall with altitude as shown by the slope of the lines on the platted diagrams depends upon the absolute humidity. In this diagram the flattest line shows the greatest rate of increase of

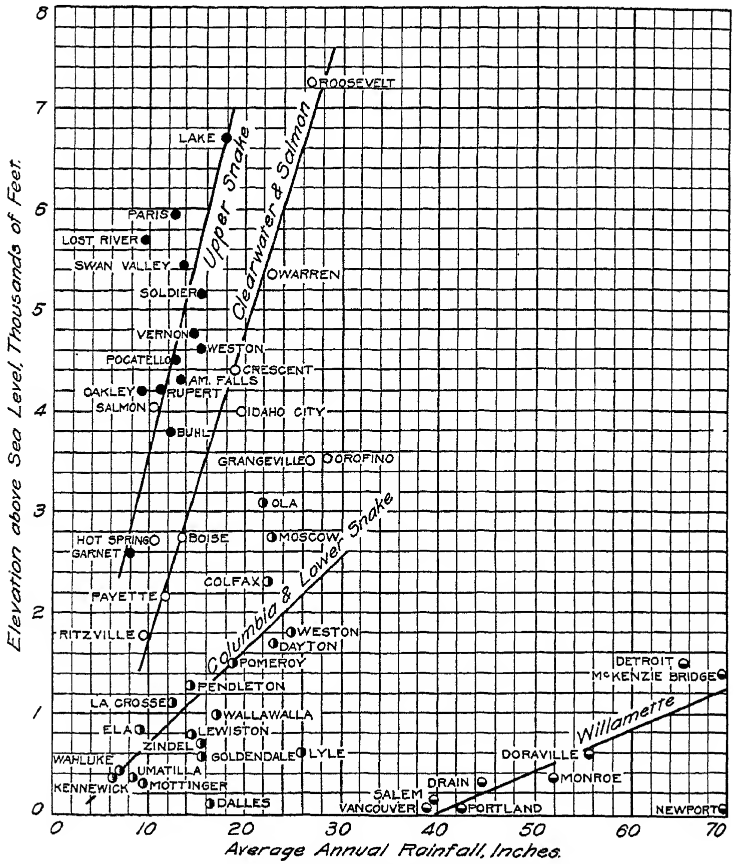

FIG. 158.—Variation of Rainfall with Altitude in Certain Valleys in Northwestern United States (see page 285).

rainfall with altitude and is for an area near the coast, and it should be noted that the slope of these lines increases and the rate of rainfall increase continually gets less and less as the river valleys considered are farther inland and the moisture content is reduced by precipitation. This tendency is exhibited by all the diagrams and shows uniformly greater rates of rainfall increase with altitude in those valleys

situated so that they receive air of greater absolute humidity. Another point to be noted is that the more broken and irregular the topography, the greater is the difficulty of determining any fixed relation between altitude and rainfall; this is shown on the diagram by the greater scattering of the plotted points. This probably is due entirely to the effect of the various topographic features in influencing the direction and moisture content of the prevailing winds.

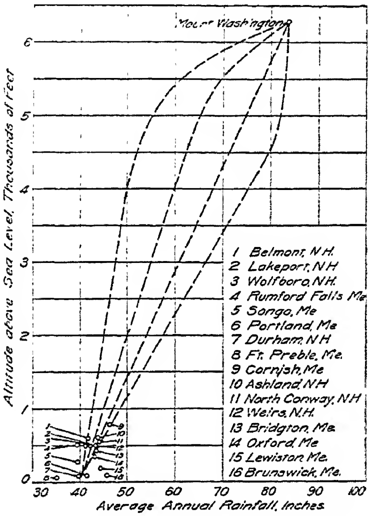

FIG. 159.—Variation of Rainfall with Altitude in the Region of Mount Washington.

A cursory examination of a topographical map on which isohyetals have been drawn will give the idea that such isohyetals fairly well define the topography of the country and demonstrate a fairly constant relation between altitude and rainfall, at least when places on either the windward or leeward side of the mountains are considered by themselves. A more detailed study of the conditions that obtain, however, will show that this apparent demonstration of a general law is largely due to the method necessarily used for drawing isohyetals with only limited data available and that the apparent uniformity of increase of rainfall with altitude is more imaginary than real. For example, Fig. 159, page 287, shows the relations that actually obtain between the average annual rainfall and the altitude of various rainfall stations in the New England States between the sea and the top of Mount Wash-

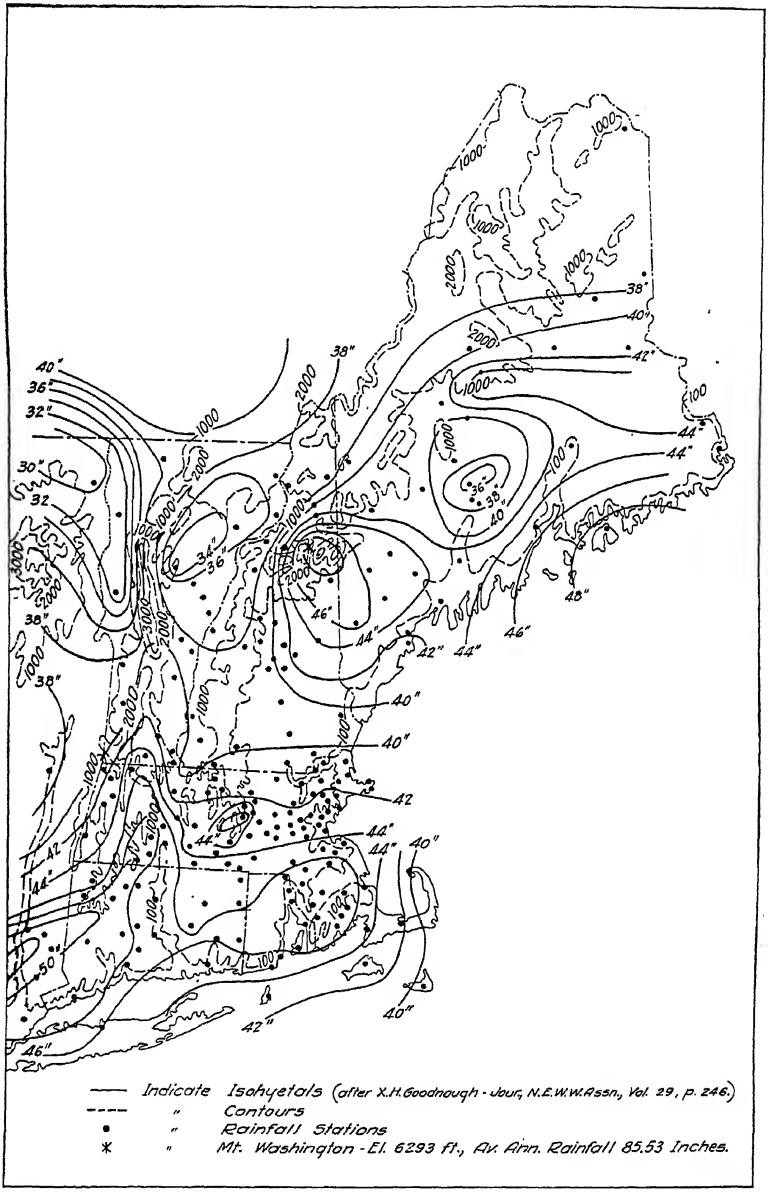

FIG. 160.—Average Rainfall of the New England States Showing Relation to Altitude and Geographical Location (see page 290).

ington. The map of this region (Fig. 160, page 288) will apparently show a somewhat constant increase of rainfall toward the summit of the mountain. If, however, we examine Fig. 159, we find that of the sixteen stations shown on the map between Mount Washington and the seas, all are below elevation 800 feet, and that Mount Washington has an elevation of about 6,200 feet. The annual rainfall of the station near sea level varies from about 35 to 46 inches and averages about 41 inches, while the average annual rainfall of Mount Washington is over 85 inches. With such an indefinite starting point and no stations between 800 and 6,200 feet, the direction of the gradient of rainfall intensity is not well established, and the dotted lines indicate gradients which may possibly obtain. It is evident that for stations between 2,000 feet and 5,500 feet, estimates of average annual rainfall may vary 10 to 25 inches or more from the truth, and that such estimates can not be made with any great degree of accuracy.

138. Factors Affecting Amount of Precipitation.—It has been shown that the intensity of rainfall is influenced by location relative to (a) sources of moisture and direction of normal winds, (b) paths of cyclonic storms, and (c) the topographical relief of the country. Mountainous countries by causing an upward flow of moist atmospheric currents produce expansion, dynamic cooling and consequent precipitation. Topographical relief is only one element in the problem; before precipitation will occur there must also be moist atmospheric currents, moving in such a direction that they will rise and expand sufficiently to produce relative humidities at and below the dew point.

The presence of moisture is more essential to precipitation than high altitudes. For example, the Pacific Coast Range of the United States, with an elevation of about 3,000 feet, induces a precipitation of 60 inches or more from the currents of moist air from the Pacific Ocean, while the higher altitudes of the Sierras (9,000 to 11,000 feet) induce a materially less rainfall from the air currents which have been considerably reduced in their absolute humidity (see Fig. 91, page 170). While the general drift of the atmosphere in the United States is easterly, it has also been shown that in general the local air currents are toward the centers of low pressure, and continually vary with the progress of the storm center. Thus in turn each source of moisture in or adjacent to the continent is induced to contribute more or less vapor to the atmosphere and to the precipitation induced by the passage of storms.

The study of almost any rainfall map will show many anomalies which cannot be satisfactorily explained. The paths of storm centers while approximately constant vary from year to year and from storm to storm. The intensities of the centers vary and the directions of the consequent incoming air currents are subject to many contingencies that are entirely fortuitous so far as human understanding is concerned. The consequent rainfalls are never the same for any two storms and still less similar for any combination of storms. This will be clearly appreciated from a study of the annual rainfall maps of Wisconsin (pages 205 to 206) an area in which the topographical relief is so small as to have little or no influence on precipitation. In the same manner that the varying storm intensity and movement combine with the sources of moisture and geographical location to produce changes in the distribution of precipitation, so the same factors combine with altitude to produce varying conditions at elevated stations and as the topographical conditions at high altitudes are more irregular, the irregularity of rainfall distribution due to altitude is more pronounced.

The mean annual rainfall map of New England (see Fig. 160, page 288) illustrates the influences of altitude, topography and geographical location. From the coast the rainfall gradually increases as the White Mountains are approached and reaches a maximum of 85.53 inches at the station on the top of Mount Washington. To the west of the White Mountains, there is a material decrease in rainfall probably due to distance from the ocean and the low intervening elevation. The rainfall is increased somewhat by the altitude of the Green Mountains of Vermont, but no data are available as to the maximum precipitation on their summits. That such an increase is possible is evident, but it is not sufficiently assured to warrant any considerable investment based on such an increase.

In the State of Maine the precipitation seems to decrease almost directly with the distance from the ocean, but westward from the coast of Massachusetts and Rhode Island there is an increase in rainfall as the distance from the ocean increases that cannot be attributed, except in a minor degree, to the effect of altitude.

To the southwest, the altitude of the Catskill Mountains undoubtedly induces increased precipitation (see Fig. 161, page 291) and yet the irregularity of the relations of altitude and intensity on the different portions of the mountains seems to be greater than would normally be accounted for by distance from the sea, and illustrates the inadequacy of our knowledge as a basis for estimating such relations without extensive precipitation data.

139. **Southern California.**—The effect of altitude on rainfall intensity often becomes more obvious in arid countries and is frequently of much greater importance in local engineering problems. Southern California while bordered by the Pacific Ocean is far from the normal

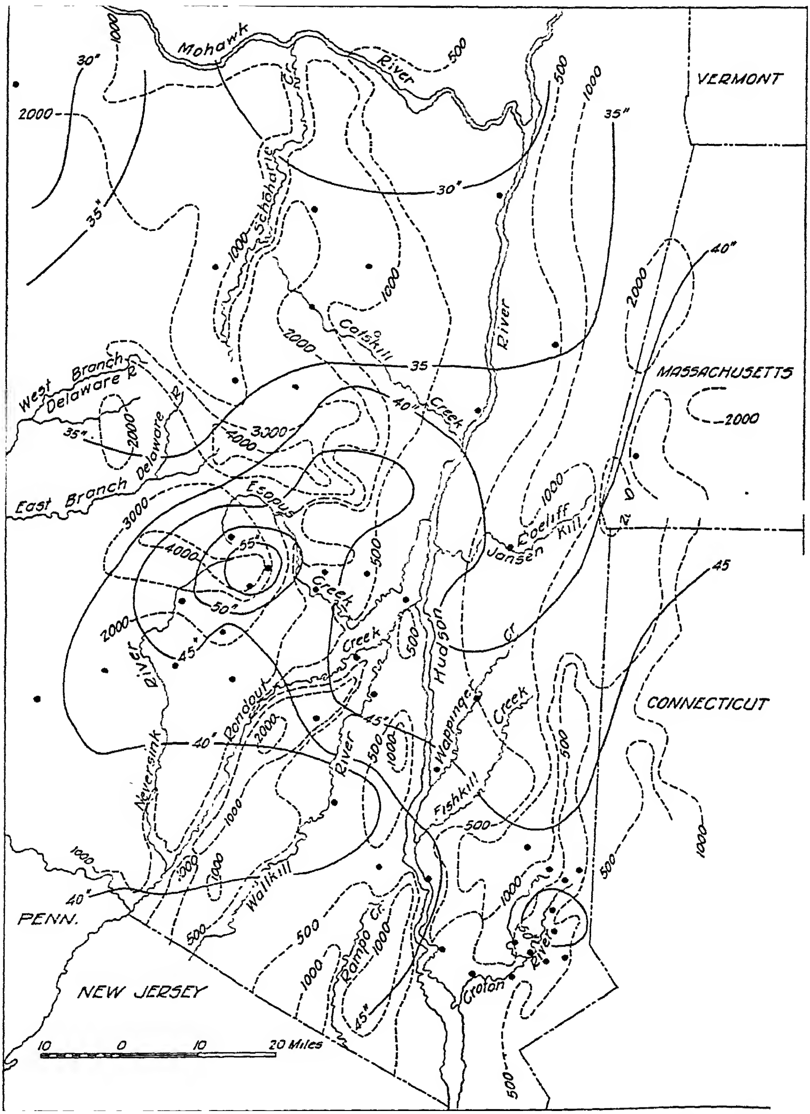

FIG. 161.—Average Annual Rainfall in the Region of the Catskill Mountains (see page 290).

paths of storm centers. The normal annual rainfall of the level country is therefore low and the importance of conserving the flow of streams for water supply and irrigation is very great. San Diego located close to the ocean has an average annual rainfall of 9.62 inches, while at Salton, about 80 miles from the coast, behind the Coast Range and about 260 feet below sea level, the average annual rainfall is about three inches. In the mountains to the eastward and near the Coast, the rainfall is greatly increased and such increase must be considered

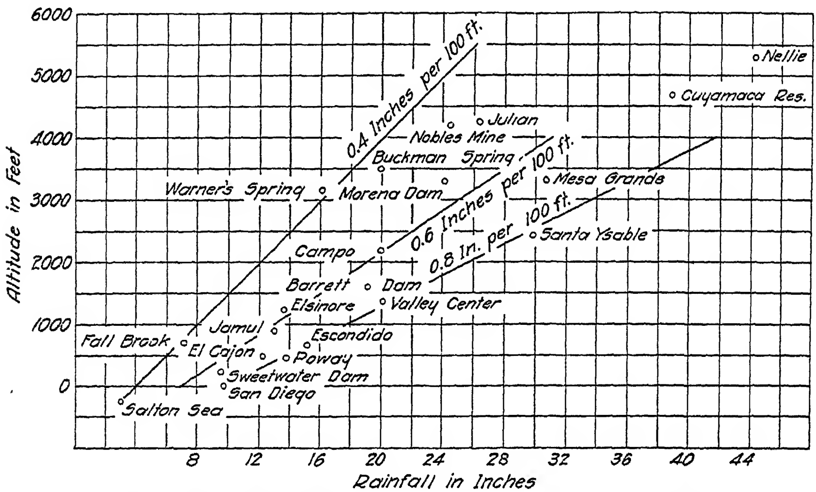

FIG. 162.—Altitude-Rainfall Diagram for San Diego and Vicinity.

in various engineering problems.[1] Considerable rainfall data are available in this region and approximate isoheytal lines may be constructed which will serve more or less as a guide in such estimates. It is found, however (see Fig. 162), that altitude alone is not a safe guide to amount of rainfall for while as a general rule for this region average annual amount increases with altitude, this increase may be from .4 inch or less per 100 feet to .8 inch or more per 100 feet of rise. These ratios represent differences in local precipitation much greater than would at first appear for it should be noted that at Warner's Springs (elevation 3,165) there is an average annual rainfall of 16 inches, while at Mesa Grand (elevation 3,300) there is an average annual rainfall of 30.70 inches. Note also the increase in rainfall from Escondido (el. 657) to Warner Springs (el. 3165) is only 0.93 inches,

[1] Construction of the Morena Dam, San Diego County, California, by M. M. O'Shaughnessy. Trans. Am. Soc. C. E., Vol. 75, page 27.

while the comparison of the rainfall of Valley Center (el. 1365) with Warner Springs shows a decrease in average annual rainfall of nearly 4 inches with a rise of 1800 feet.

FIG. 163.—Topographic Map of San Diego and Vicinity Showing Relative Locations of Rainfall Stations.

In making estimates of the rainfall at intermediate stations within this area, great care is therefore needed to secure results which are even approximately correct.

The mean annual rainfall (1910) at various stations in San Diego County and vicinity is given in Table 31, together with the elevation

of the station.[2] A topographical map, based on the maps of the U. S. Geological Survey, showing the relative locations of rainfall stations is shown in Fig. 163.

On this map all areas lying above elevation 2,000 feet are cross hatched.

TABLE 31.

Rainfall Stations, San Diego County, California, and Vicinity.

	Length of observation Period, years	Elevation above sea level Feet	Average annual rainfall Inches
Nellie	7	5,300	44.26
Cuyamaca Reservoir	21	4,677	38.84
Julian	28	4,250	26.36
Noble's Mine	3	4,200	24.5
Buckman Springs	2	3,500	19.90
Mesa Grande	5	3,300	30.70
Morena Dam	5	3,300	24.15
Warner's Springs	4	3,165	16.08
Santa Ysabel	10	2,983	24.17
Campo	31	2,189	19.98
Barrett Dam	5	1,600	19.07
Valley Center	26	1,365	20.03
Elsinore	12	1,234	13.64
Jamul	6	900	13.00
Fallbrook	27	700	17.14
Escondido	14	657	15.15
El Cajon	10	482	12.24
Foway	29	460	13.79
Sweetwater Dam	20	238	9.52
San Diego	53	87	9.62
Salton Sea	30	—260	3.

TABLE 32.

Rainfall Stations in Southern Arizona and New Mexico.

Station	Length of observation period, years	Altitude above sea level, feet	Average annual rainfall inches
Luna, N. M.	14	7,300	15.94
Rosedale, N. M.	11	6,900	19.26
Flagstaff, Ariz.	22	6,907	22.96
Bluewater, N. M.	14	6,732	9.53
Ft. Bayard, N. M.	46	6,152	15.42
Pinto, Ariz.	10	5,660	11.49
Snowflake, Ariz.	12	5,644	10.27
Lake Valley, N. M.	10	5,413	14.71
Ft. Buchanan, Ariz.	4	5,330	21.58
Bisbee, Ariz.	25	5,350	18.44
Prescott, Ariz.	48	5,320	17.21
Ft. Apache, Ariz.	41	5,200	17.87
Ft. Huachuca, Ariz.	30	5,100	17.06
Holbrook, Ariz.	24	5,069	9.30

[2] Ibid, page 54.

TABLE 32—*Continued.*

Rainfall Stations in Southern Arizona and New Mexico.

Station	Length of observations period, years	Altitude above sea level, feet.	Average annual rainfall, inches
Ft. Grant (Bonita) Ariz.	39	4,916	14.27
Alma, N. M.	18	4,800	15.65
Jerome, Ariz.	17	4,743	18.92
Tombstone, Ariz.	17	4,550	13.85
Pinal, Ariz.	23	4,520	23.45
Oracle, Ariz.	19	4,502	19.50
Gage, N. M.	16	4,420	10.21
Mimbres, N. M.	..	4,339	18.42
Deming, N. M.	39	4,333	10.03
Tonto, Ariz.	13	4,300	15.15
Cochise, Ariz.	25	4,250	11.69
Lordsburg, N. M.	26	4,245	9.36
Wilcox, Ariz.	35	4,203	10.91
Gila, N. M.	8	4,040	14.50
Douglas, Ariz.	20	3,930	15.03
Nogales, Ariz.	17	3,830	13.97
Breckinridge, Ariz.	6	3,800	17.03
Bowie, Ariz.	35	3,756	14.10
Globe, Ariz.	15	3,625	16.71
San Simon	25	3,609	7.86
Clifton, Ariz.	25	3,584	13.55
Benson, Ariz.	34	3,523	9.47
Kingman, Ariz.	13	3,326	11.02
Vail, Ariz.	26	3,241	10.69
Verde, Ariz.	22	3,160	13.13
Ft. Thomas, Ariz.	26	2,816	11.46
Thatcher, Ariz.	17	2,800	10.23
Rice, Ariz.	33	2,540	11.30
San Carlos, Ariz.	25	2,456	12.91
Tucson, Ariz.	49	2,400	11.74
Cline, Ariz.	14	2,300	15.49
Dudleyville, Ariz.	23	2,204	14.59
Wickenberg, Ariz.	14	2,072	9.47
Redrock, Ariz.	12	1,864	11.18
Florence, Ariz.	18	1,493	9.88
Casa Grande, Ariz.	26	1,396	5.76
McDowell, Ariz.	23	1,250	10.38
Mesa, Ariz.	19	1,244	8.78
Maricopa, Ariz.	36	1,180	6.19
Phoenix, Ariz.	24	1,100	8.00
Buckeye, Ariz.	24	980	7.34
Sentinel, Ariz.	16	685	4.00
Gila Bend, Ariz.	25	787	5.82
Mohawk, Ariz.	28	538	3.32
Aztec, Ariz.	9	492	3.92
Parker, Ariz.	19	353	4.82
Yuma, Ariz.	35	140	3.00

140. **Southern Arizona.**—The relation of altitude to mean annual rainfall intensity in Southern Arizona is shown by Fig. 164, page 296. The solid inclined lines on this figure indicate rates of increase of

rainfall with altitude, while the dashed lines show rules or formulas suggested for this region. The approximate topographical conditions surrounding the various stations are shown in Fig. 165, page 297, in

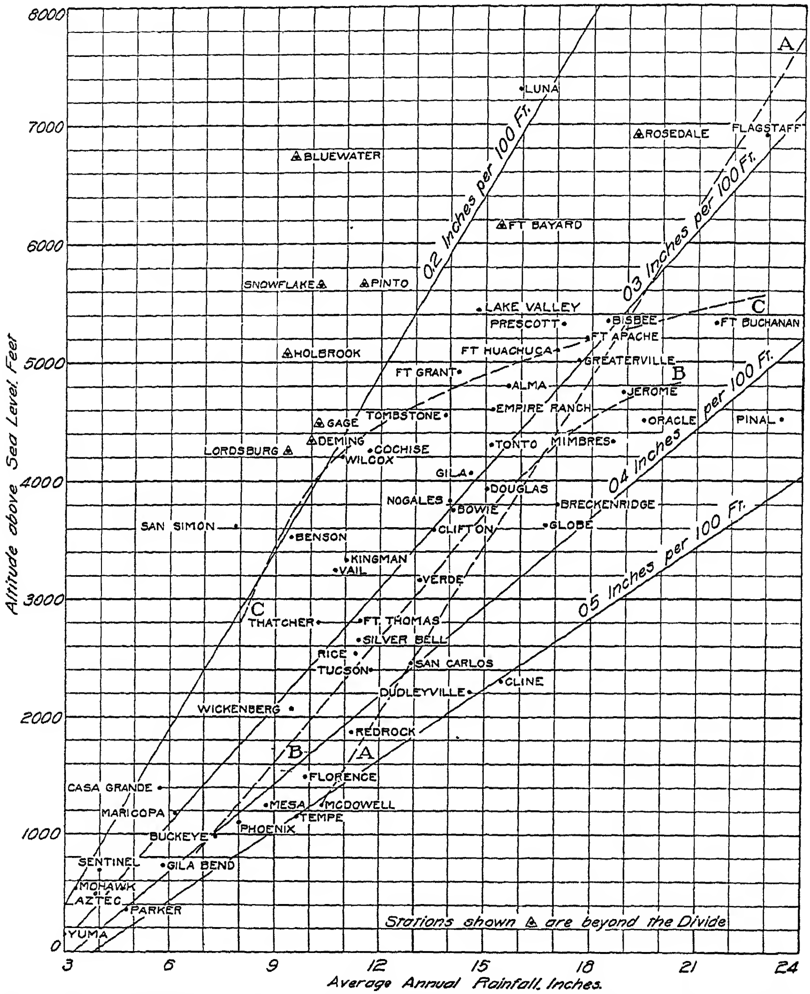

FIG. 164.—Altitude-Rainfall Diagram for Southern Arizona (see page 295).

which the areas lying above elevations of 5,000 feet are shown cross hatched. In Arizona as in Southern California the general increase of intensity with altitude is at once apparent from Fig. 164; but a brief examination of the data will indicate the great danger of error in any estimate of the average intensity of the annual rainfall for inter-

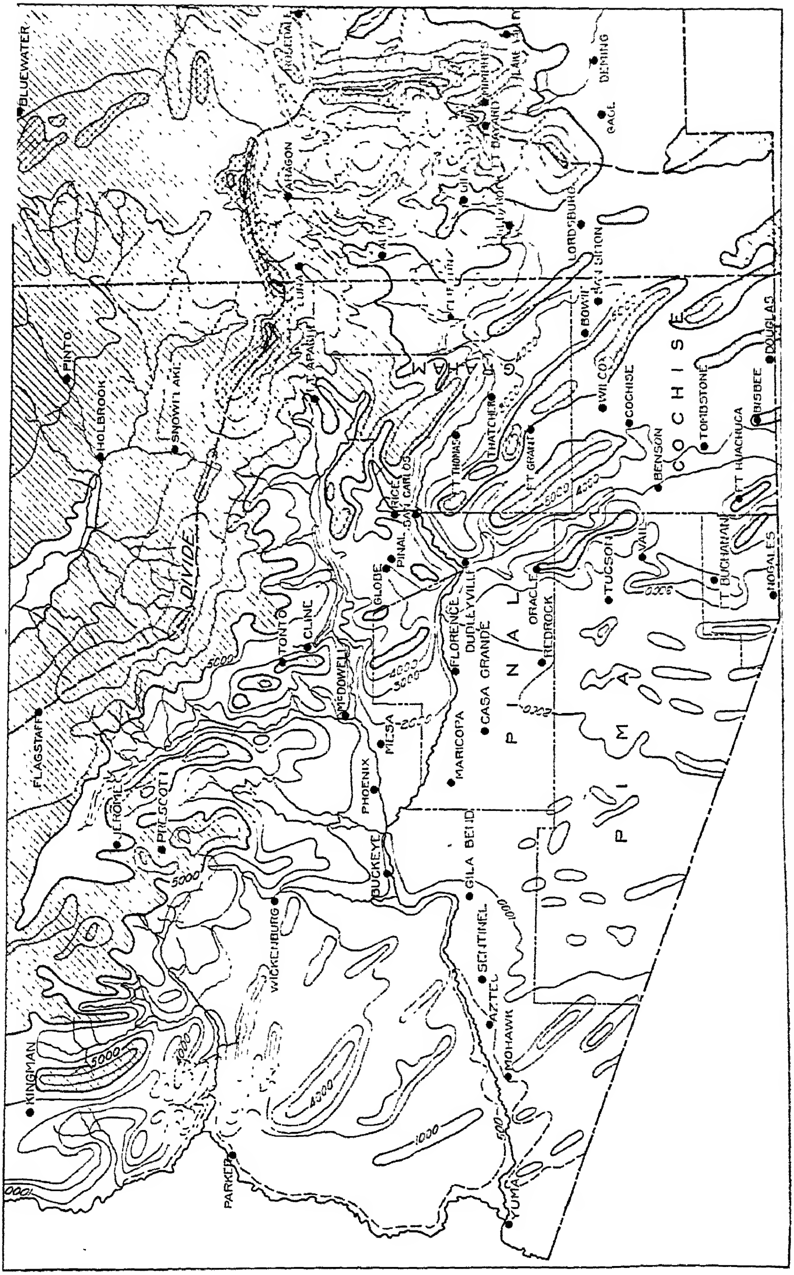

FIG. 165.—Topographic Map of Southern Arizona and Southwestern New Mexico (see page 296).

mediate stations. The great range in the average amount of annual rainfall at various stations beween 4,000 and 5,000 feet in altitude should be noted. Table 32 gives the rainfall stations in the area together with the period of observation, altitude above sea level and mean annual rainfall of each station. Several attempts have been

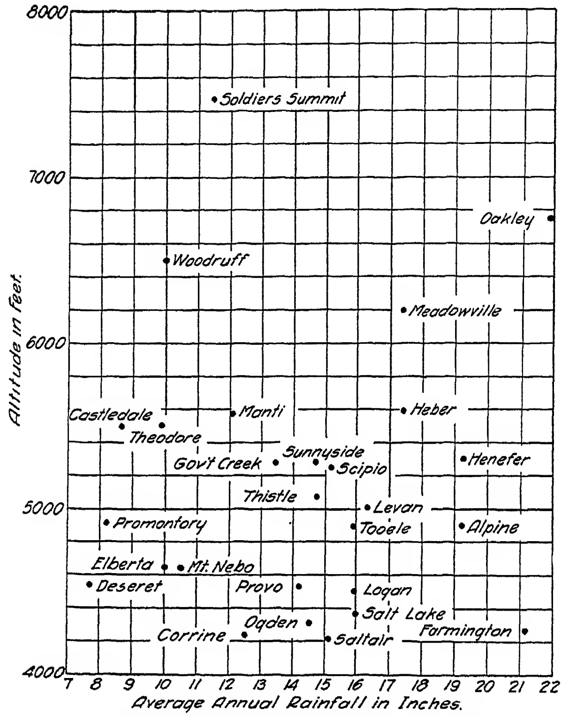

FIG. 166.—Altitude-Rainfall Diagram for Southern Utah.

made to establish definite rules for calculating these relations for parts of this territory, which are discussed in Section 143.

141. **North Eastern Utah.**—The distinct increase of average annual rainfall with altitude is not always as definite as in the cases discussed in Sections 139 and 140. In northeastern Utah west of the Wasatch Mountains, the Great Salt Lake seems to have an influence on the rainfall of the stations to the east which almost entirely obscures the effect of altitude. Here a few miles distance from the lake seems to have a much greater effect than a considerable difference in altitude. These relations are shown in Fig. 166, and the approximate topographical conditions are shown in Fig. 167 in which the cross hatched por-

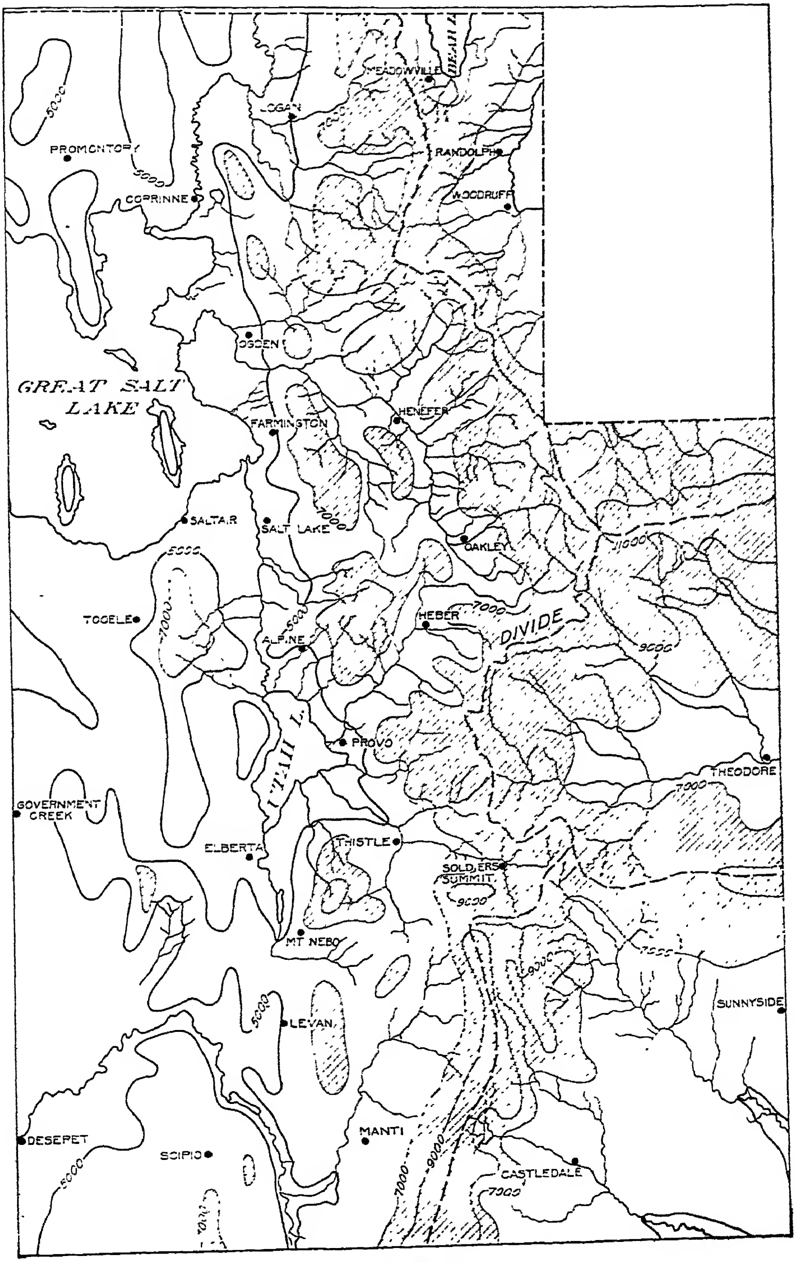

Fig. 167.—Topographic Map of Northeastern Utah.

[illegible] feet. The effects of Great Salt [illegible] precipitation at stations south [illegible] paths of atmospheric movement [illegible]. The influences of locations beyond the [illegible]. It should also be noted that a line passing

TABLE 33.

[illegible] stations in Utah.

Station.	Length of observations period, years	Elevation above sea level, feet	Average annual rainfall, inches
Soldier's Summit	12	7,425	12.10
Oakley	4	6,750	21.2
Woodruff	4	6,500	10.01
Meadowville	14	6,200	17.41
Heber	22	5,620	17.46
Manti	29	5,575	12.10
[illegible]	3	5,507	9.92
Castledale	16	5,500	8.63
Henefer	15	5,301	19.30
Sunnyside	5	5,282	14.86
[illegible] Creek	14	5,277	13.44
Scipio	29	5,260	15.22
Thistle	21	5,075	14.76
Levan	19	5,010	16.38
[illegible]	30	4,913	8.23
Alpine	8	4,900	19.28
Tooele	19	4,900	15.93
Elberta	13	4,650	10.06
Mt. Nebo	8	4,650	10.53
Deseret	20	4,541	7.88
Provo	21	4,532	14.20
Logan	24	4,507	15.97
Salt Lake	41	4,366	16.03
Ogden	44	4,310	14.55
Farmington	10	4,267	21.17
Corinne	45	4,240	12.51
Saltair	11	4,220	15.15

near Saltair, Heber and Oakley, seems to indicate a certain approximate relation of altitude to rainfall intensity in one direction, conclusions from which would be quite different from those which would be drawn from a similar line drawn near Saltair, Provo, Thistle and Soldier's Summit. It should also be noted that the difference in rainfall between Salt Lake City and Alpine or Farmington cannot reasonably be attributed to distance from the lake or difference in altitude but must be due to the local direction of moist air currents not to be accounted for without much fuller information than is here available. Table 33 gives the rainfall stations in this area together with the period

of observation, altitude above sea level, and the mean annual rainfall of each station.

142. **The Relations of Altitude and Rainfall During Single Storms.**—The relation of average annual rainfall to altitude is modified by the many fortuitous circumstances which surround the occurrence of the numerous local and general rainstorms of which these annual means are made up. A study of single storms may give a more

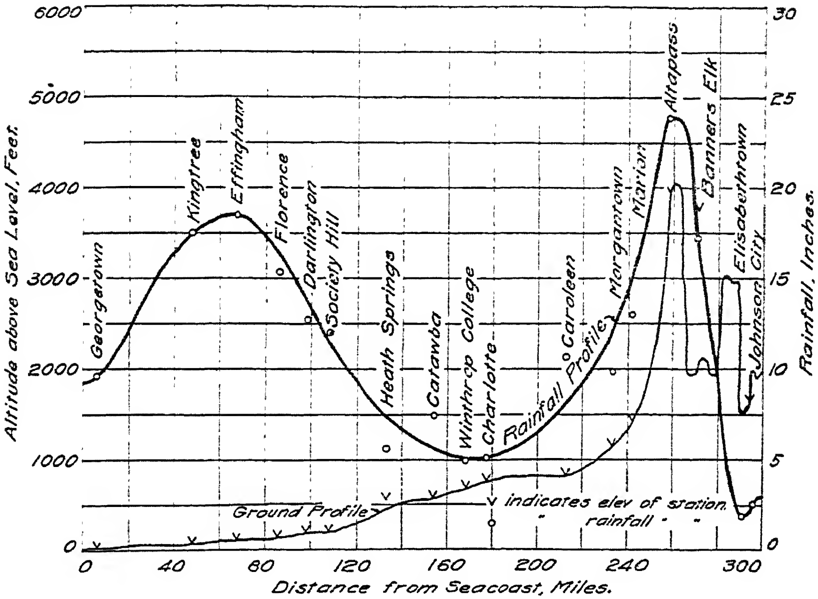

FIG. 168.—Topographic and Rainfall Profiles for the Storm of July 14–17, 1916, in the Carolinas (see page 302).

distinct idea of the influences of various factors on the main problem.

The great storm which occurred in the South Atlantic and East Gulf States, July 14 to 17, 1916, has been briefly discussed (see Section 85) and illustrated (see Figs. 95 and 96, pages 174 and 175). As is ordinarily the case with rainstorms which accompany West Indian hurricanes, a considerable rainfall occurred close to the point at which the hurricane path first encountered the land. In most cases the rainfall of the interior rapidly decreases as the distance from the Coast increases. In this case, however, the hurricane moved directly toward the southeastern spur of the Alleghenies and was apparently dissipated thereby. The altitudes encountered induced a still heavier rainfall on the mountain slope and a record precipitation

h. Fig. 1?8 shows the profile of the land surface Georgetown, S. C. to Altapass, N. C. On this the location and comparative elevation of various along the line of this profile, and above each is rainfall that occurred during his storm. This

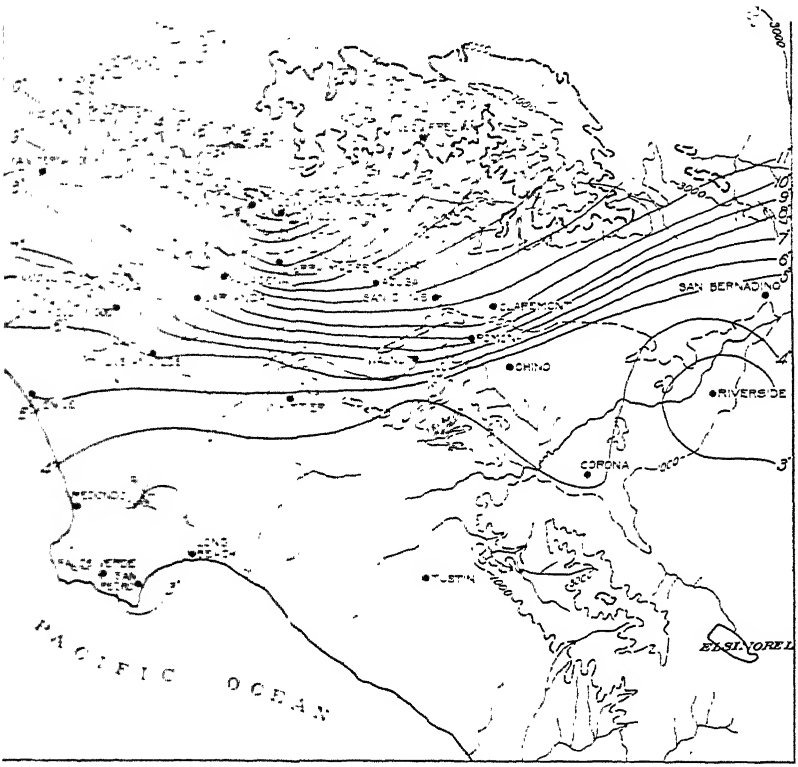

Fig. 163.—Topographic and Rainfall Map of the Los Angeles District (see page 303).

profile shows the great rainfall which occurred closely adjacent to the coast and the greater rainfall on the mountains. A heavy rainfall was apparently also induced in the region just beyond the divide, and the radical decrease in precipitation at Elizabethtown about 30 miles ther on is also shown.

An unusually heavy rainstorm occurred in the Los Angeles district Southern California, Feb. 18 to 21, 1914. This rainfall was occasioned by a storm the center of which slowly approached the northern Pacific Coast, passed over Port Crescent Feb. 22, and was appar-

ently dissipated in the mountains. Its slow movement gave rise to far reaching effects, as is shown by the unusual precipitation in Southern California. Fig. 169 is a topographical map of the Los Angeles region on which have been drawn isohyetals [3] which indicate in a general way the effect of elevation on the rainfall intensity. Distance from the sea here seems to have little effect, the apparent factors being

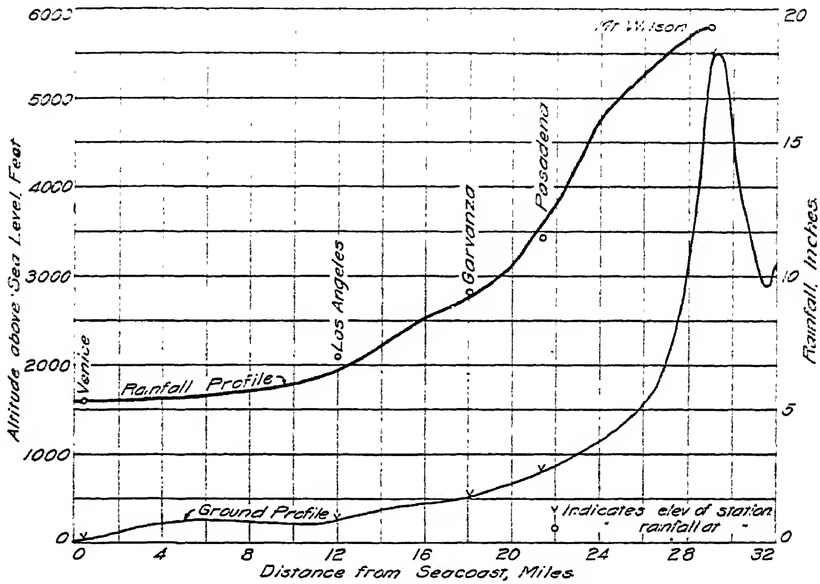

FIG. 170.—Topographic and Rainfall Profiles for the Los Angeles District.

the direction of the air currents and altitude. Fig. 170 shows a profile of surface elevations and of rainfall intensities based on the records of stations closely adjoining a line drawn from San Pedro to Mount Wilson. Table 34 gives the rainfall stations in this area together with the period of observation and altitude above sea level at each station.

It is pertinent and instructive to add that the relations of altitude to intensity of precipitation as indicated by the records at Los Angeles and Mount Lowe are not alone indicated by individual rain storms but are also clearly shown by the average monthly and annual precipitation at these two stations as shown graphically by Fig. 171.[4] It is to be noted, however, that the rainfall for each individual storm or for

[3] Flood Studies at Los Angeles, F. A. Carpenter. Monthly Weather Review, 1914, page 385.

[4] Ibid, page 385.

TABLE 34.

Rainfall at Stations Near Los Angeles Cal,

Station	Elevation, feet	Jan. 12–19, 1916 inches	Jan. 22–29, 1916 inches	Feb. 18–21, 1914 inches
Avalon	[illegible]	....	....	3.45
Azusa	34[illegible]	12.30	4.56	13.26
Bear Valley Dam..	4,0[illegible]	....	....	10.83
Chino	714	....	....	4.81
Claremont	1,200	10.80	4.74	10.92
Cleghorn Canyon ..	4,[illegible]37	....	....	17.85
Corona	615	8.28	6.16	4.31
Devil Canyon	....	....	....	8.63
East Highlands ...	1,334	....	....	4.85
Fillmore	470	....	....	6.44
Garvanza*	536	....	....	9.41
Highland	1.316	....	....	5.68
Hollywood*	400	....	....	6.75
Long Beach	47	....	....	3.24
Los Angeles	233	6.90	3.49	7.07
Mill Creek	2,950	7.36	6.16	11.10
Mt. Lowe	3.500	11.40	3.76	19.20
Mt. Wilson	5.850	13.40	5.90	19.40
Orange	176	....	....	3.55
Palm Springs	584	....	....	3.90
Palos Verde	1.1[illegible]	....	....	3.87
Pasadena	827	8.82	3.49	11.44
Pomona	857	10.50	4.92	9.60
Redlands	1,352	5.84	3.33	4.26
Redondo	16	....	....	3.51
Riverside	851	4.80	3.53	2.79
San Antonio Canyon	1,888	....	....	12.25
Pacoima	1,066	8.47	3.55	8.88
San Bernardino ...	1,054	8.75	4.57	4.71
San Dimas	909	....	....	11.29
San Pedro	19	3.00	2.60	2.03
Santa Monica	110	7.14	4.13	5.50
Sierra Madre	1,400	10.21	4.27	15.56
Squirrel Inn	5,280	27.78	10.86	16.29
Tustin	125	4.01	3.83	3.52
Valyermo	3,750	5.16	0.58	5.57
Venice	25	....	....	5.16
Ventura	50	....	....	10.21
Walnut	600	....	....	6.96
Whittier	246	....	....	5.02

*Suburb of Los Angeles.

each individual month or year does not uniformly show such relations. (See Table 35.)

143. Rules for Estimating Relations of Altitude to Rainfall.—While it has been possible to discuss in this chapter the relation of altitude to rainfall in only a few local districts, enough has been said and shown to emphasize the fact that any rule for estimating such relations

TABLE 35

Comparison of rainfall of Los Angeles and Mt. Lowe

		Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov	Dec.	
1896	Los Angeles	3.23	T	2.97	0.19	0.30	T	0.02	0.01	T	1.30	1.66	2.12	11.80
	Mt. Lowe...	2.85	0.10	4.10	0.60	0.30	0.07	0.10	0.10	0.00	2.35	1.55	2.17	14.16
1897	Los Angeles	3.70	5.62	2.31	0.02	0.10	T	T	0.00	0.00	2.47	0.01	0.05	14.28
	Mt. Lowe ..	6.42	7.47	6.67	0.19	0.87	0.10	0.15	0.00	0.00	2.57	0.40	0.22	25.06
1898	Los Angeles	1.26	0.51	0.98	0.03	1.75	T	0.07	T	0.02	0.09	T	0.12	4.83
	Mt. Lowe ..	1.55	2.22	1.65	2.70	2.17	0.00	0.00	0.00	0.25	0.30	0.90	0.08	11.82
1899	Los Angeles	2.64	0.04	1.81	0.18	0.04	0.58	0.00	0.01	T	1.56	0.90	0.93	8.69
	Mt. Lowe ..	3.29	0.00	3.40	0.20	1.90	0.40	0.00	0.00	0.00	3.00	2.85	2.14	17.18
1900	Los Angeles	1.17	T	0.99	0.54	1.81	T	T	T	T	0.26	6.53	T	11.30
	Mt. Lowe ..	5.50	5.03	2.90	2.15	4.05	0.40	T	0.00	0.25	1.66	11.71	0.00	33.65
1901	Los Angeles	2.49	4.38	0.45	0.65	1.50	T	T	0.09	0.03	1.88	0.46	0.00	11.96
	Mt. Lowe ..	7.55	5.42	1.18	1.14	4.45	0.75	0.00	0.00	0.00	4.18	1.05	0.23	25.95
1902	Los Angeles	1.62	3.35	2.98	0.16	0.03	T	T	T	T	0.40	2.08	2.50	13.12
	Mt. Lowe ..	1.88	3.48	5.97	1.35	0.53	0.30	0.00	0.00	0.00	0.93	3.68	2.14	20.03
1903	Los Angeles	2.10	1.52	6.93	3.77	T	0.02	0.00	T	0.43	T	0.00	T	14.77
	Mt. Lowe													
1904	Los Angeles	0.14	2.68	4.50	0.97	T	T	T	0.17	0.28	0.69	0.00	2.45	11.88
	Mt. Lowe ..	0.00	4.02	6.92	2.10	0.20	0.00	0.00	1.27	1.50	0.00	0.00	1.98	17.99
1905	Los Angeles	2.57	6.06	6.00	0.35	0.95	0.00	0.00	0.00	T	0.08	2.98	0.20	19.19
	Mt. Lowe ..	4.02	12.53	10.50	1.07	4.01	0.00	0.00	0.00	0.00	0.24	3.74	0.12	36.23
1906	Los Angeles	3.85	2.47	7.35	0.69	1.02	0.01	0.02	0.03	0.05	0.00	0.55	5.12	21.46
	Mt. Lowe ..	4.55	3.80	18.66	2.28	3.50	0.00	0.10	0.22	0.00	0.00	1.04	11.85	41.99
1907	Los Angeles	7.02	1.83	4.12	0.16	0.07	0.03	0.00	0.00	T	1.18	T	0.88	15.30
	Mt. Lowe ..	12.83	3.60	7.24	1.90	0.89	0.94	0.00	0.00	0.00	3.36	0.05	1.67	32.48
1908	Los Angeles	5.04	3.66	0.18	0.52	0.25	0.00	T	0.08	1.22	0.25	1.08	1.46	13.74
	Mt. Lowe ..	6.84	5.56	1.02	1.90	0.95	0.00	0.00	0.00	2.48	0.80	0.75	2.13	22.43
1909	Los Angeles	7.27	5.20	2.51	T	0.00	0.11	0.00	T	0.04	0.28	1.51	7.00	23.92
	Mt. Lowe ..	14.22	11.94	7.38	0.56	0.03	0.75	T	[1] 0.02	0.15	1.40	3.10	18.98	[2] 51.53
1910	Los Angeles	1.53	0.11	1.86	0.30	0.00	0.00	0.04	T	0.01	0.82	0.15	0.07	4.89
	Mt. Lowe ..	1.40	0.14	3.80	0.27	0.02	0.00	T	0.0	0.00	1.05	1.57	[1] 0.07	[3] 8.32
1911	Los Angeles	6.70	2.91	5.15	0.28	0.02	0.03	T	0.00	1.23	0.16	0.10	1.27	17.85
	Mt. Lowe ..	15.76	4.37	5.95	1.90	0.25	0.00	0.00	0.00	2.00	0.20	0.22	1.25	31.90
1912	Los Angeles	0.07	0.00	6.99	1.66	0.12	0.00	T	0.00	0.01	0.56	0.35	0.03	9.78
	Mt. Lowe ..	0.50	0.00	8.12	2.67	0.87	0.00	0.00	0.00	0.00	2.20	0.60	T	14.96
1913	Los Angeles	2.01	9.16	0.33	0.35	0.05	0.58	T	T	0.03	T	3.00	1.66	17.17
	Mt. Lowe ..	3.16	11.60	0.76	0.98	T	1.65	0.05	0.00	0.05	T	4.00	2.85	25.10
1914	Los Angeles	10.35	7.04	0.58	0.47	0.43	0.09	0.01	0.00	0.00	0.31	0.20	3.73	23.21
	Mt. Lowe ..	12.70	19.20	1.30	2.12	0.98	0.20	T	0.00	0.00	1.43	T	5.80	43.73
1915	Los Angeles	5.42	5.09	0.60	0.81	0.88	T	0.00	0.00	T	0.00	1.35	2.52	16.67
	Mt. Lowe ..	8.60	8.00	1.22	2.44	2.45	0.00	0.00	0.00	0.10	0.00	2.00	2.70	27.51
1916	Los Angeles	13.30	1.82	0.90	T	0.03	0.00	0.00	T	0.77	2.71	0.09	3.67	23.29
	Mt. Lowe	19.86	2.87	4.15	0.00	0.00	0.00	0.00	0.00	1.80	5.00	0.30	6.40	40.38

[1] Estimated

[2] Includes estimated total for August

[3] Includes estimated total for December

must be purely local. Even in these cases rules must be regarded as subject to possible exceptions which may greatly affect the accuracy of estimates based thereon. The very statement of the attempted rule often shows the difficulties in its application.

On the north slope of the French Alps, at the elevation of 1,500 me-

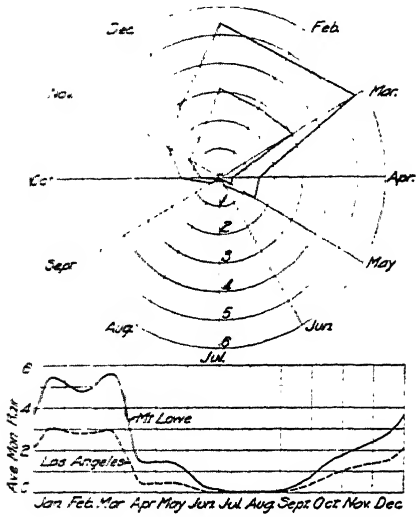

FIG. 171.—Average Rainfall at Los Angeles and Mt. Lowe (see page 303).

ters, an average rainfall of 1,500 mm has been observed; and it is assumed that as a general average, the rainfall in the regions above 1,500 meters increases by 150 to 250 mm for every 100 meters elevation. Certain small regions may, of course, have results that differ from this arbitrary rule.[5]

In Austria the plains have the least rainfall. In Central Bohemia and in Mähren and Lower Austria, etc., the yearly rainfall decreases to 200 to 300 mm. The following table, compiled by Bebber, shows the effect of elevation upon rainfall:[6]

From 100– 200 m. above sea level	583 mm.
200– 300	650
300– 400	696
400– 500	782
500– 700	852
700–1,000	995
1,000–1,200	1,308

[5] Der Wasserbau, 1907, Th. Koehn.
[6] Frederick Kulturtechnischen Wasserbau.

Usually attempts to formulate the relation of rainfall to altitude have been expressed by a straight line equation:[7]

$$R' = R + K\frac{A}{100}$$

in which R′ and R are average annual rainfalls at the higher and lower points respectively, A is the difference in altitude in feet, and K is a constant for the region. Values of K range from two-tenths to eight-tenths of an inch in the West, six-tenths being frequently used for the Sierras of California. A value of 0.21 was derived by Mr. J. B. Lippincott for the Gila and Salt River Basins in Arizona.[8] The rule which was formulated by Lippincott about 1899 still seems in the light of seventeen years additional data to apply with reasonable accuracy to the local conditions in this valley. It should be used, however, only after careful consideration of the local condition of the area for which an estimate is to be made.

Prof. G. E. P. Smith has sought to establish such relations for certain areas in Southern Arizona.[8] He has suggested two curves, one for Cochise and Graham Counties, and the other for Pima and Pinal Counties. The author has been unable to ascertain any adequate reason for the differentiation between these Counties, or for the belief that there is any increase in annual rainfall above the 4000 foot contour.

144. **General Conclusions.**—While in general rainfall will increase with altitude, it is dangerous to assume that this will always be the case, as there are many exceptions to this rule. Where the rule holds, the amount of such increase is difficult and often impossible to determine.

An assumption of large runoff for mountain streams based solely upon elevation where no records of mountain rainfall or runoff are available, is unsafe and does not warrant large investments in projects based upon such assumptions.

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CHAPTER XIII

GEOLOGICAL AGENCIES AND THEIR WORK

145. **Hydrological Influence of Topography and Geology.**—The geology of a district and its accompanying topographical and stratigraphical conditions greatly modify its hydrological phenomena. Sharp topographical relief, as shown in Chapter XII, exerts a notable influence, quantitatively uncertain, by increasing precipitation on the windward side and decreasing precipitation on the leeward side of considerable elevations. The character of the material and the dip of the strata have had a marked influence on the trend of the development of streams, and still have such influence on the effect of the flow on the denudation of the exposed strata.

The structure, extent of outcrop and slope of the strata have an important effect on the disposal of rain waters and greatly modify the relative amounts of evaporation, absorption and surface flow. These same factors, together with the amount and distribution of the precipitation received on the exposed outcrops of the strata, are the controlling elements which modify the presence and flow of underground waters. The surface slope of the country and the character of the rocks composing the drainage area, together with the amount and distribution of the precipitation, are controlling factors in the character of runoff or stream flow. All of these factors are in turn modified by geographical and climatic conditions. A study of local geological history gives indications of the possible or probable character and extent of the underlying strata and is prerequisite to intelligent local investigations.

The present conditions have been brought about through agencies that are still active and which are still impressing their influence on the earth's surface. While the activity of these agencies may have been modified by changes in climatic and other conditions, the general nature of their action remains unchanged and a study of their past effect will give an intelligent basis for the type of construction necessary to utilize these agencies for the benefit of mankind.

For a proper knowledge of the hydrological conditions of any district, an understanding of historical and general geology and of the character of the agencies and sequence of events that led up to the local geological conditions that now obtain, is frequently indispensable.

In a general treatise on hydrology it is possible to discuss geology in a very general way only, and to consider in greater detail but still in a most general way, a few of the most important factors and conditions which influence or control the problems of the hydraulic engineer. The knowledge of general geology necessary for a clear conception of many problems in engineering, as well as the detailed study of the more or less local conditions which for successful results must be investigated and understood, can be secured by the engineer from the many special treatises on these subjects.

146. **Outline of Causes Productive of Topographical and Geological Changes.**—The following is a summary of the agencies that have been active causes of the evolution of the earth's surface from past to present structure and form. These agencies are still active and operative, and an appreciation and knowledge of them are essential in order that the engineer may design his structures for stability and permanency so far as possible.

A. *Factors of Disintegration:*

(a) Rock Texture:

Resistant—Capable of withstanding erosive agencies for considerable periods.

Yielding—Easily eroded.

(b) Vegetation:

Wedging action of plant roots. Decay of vegetation results in the formation of acids which increase solvent power of water.

Retards surface erosion of soil where thick enough to form a protective covering.

B. *Factors of Erosion, Corrasion and Transportation:*

(a) Crust Movements:

Unequal settlements resulting in oceans and continents.

Upheavals resulting in islands and mountain ranges.

Subsidence. Deep sea inlets, bays, etc.

Volcanic. Limited but marked upheavals and subsidence, and ejection of molten matter.

(b) Precipitation and Moisture:

Concentration of rainfall tends to increase corrasion and transportation powers by increasing volume and velocity of runoff.

Humidity of atmosphere tends to check sudden and considerable variations in temperature.

Rivers:

Powers of corrasion, transportation and deposition depend on velocity and volume of flow and the material forming the river bed and banks.

Ice:

Corrasion by glaciers and avalanches.

Transportation by river ice, glaciers and avalanches.

(c) Ocean and Lake Movements:

The waves on the lakes and seas erode the shores against which they impinge.

The lake and ocean currents transport the materials eroded by the waves or discharged by the rivers and build up extensions to the land and independent banks in the open water where conditions favorable to deposition occur.

(d) Atmospheric Movements:

Less important than precipitation except in regions of low rainfall.

Direct effect great in modifying evaporation and precipitation.

Shifting of sand dunes.

In moist climates dries earth to dust and transports dust and sand.

In arid regions there is less rock decay and less vegetation to anchor the products of decay, action of wind erosion in carving rocks (sand blast effect) is often great.

Creates waves and currents.

147. **Rock Structure and Texture.**—The diastrophic movements which have taken place since the indurated formations were first laid down have resulted in the development of joints and fissures in all rock masses at and near the surface which have given greater or less access to the agents of disintegration into exposed rock masses. Rocks of massive structure with few joints and fissures and with small exposures and gentle slopes, and which are protected by mantle coverings, disintegrate slowly. On the other hand, bare rocks with open joints and fissures or those composed of alternate beds of hard and soft material having steep slopes or existing as exposed clefts from which loosened material is rapidly removed, are quickly disintegrated.

In the same manner the texture of the rock has a considerable influence upon the rapidity of disintegration. If the rock is close grained,

impervious, composed of insoluble material and of a physical quality capable of standing erosive action, disintegration is slow. Pervious rocks of loose grain, composed of soluble material which is easily eroded, rapidly yield to disintegration.

148. **Erosion.**—In order to understand the causes of topographical and geological changes, the extension and reduction of continental areas, the work of waves, tides and currents, the formation, extension and extinction of lakes, the development of drainage systems, the work of rivers and streams, and the consequent changes in the topography of their drainage areas, it is necessary to have a clear understanding of the manner in which the elements combine their actions and the methods by which they accomplish their work.

There are three principal methods by which the elements of erosion are continually reducing the heights of land toward what is termed the base level, which is approximately sea level, namely: weathering, corrasion, and transportation.

Weathering is that continual decomposition and disintegration of the rock formations by which they are broken into fragments and reduced to the finest particles.

Corrasion embraces the methods by which the action of running water reduces the masses of rocks by abrasion and solution.

Transportation is the term applied to the conveyance from their original positions of fragments and particles produced by weathering and corrasion.

The rapidity with which the various processes of erosion are carried on depends principally upon the texture of the deposits and on climate, and varies particularly with the abundance of rainfall.

149. **Weathering.**—The weathering of rocks may be the result of chemical or mechanical processes. Through the agency of chemical action, portions of the cementing materials which bind the rock into a homogeneous mass are dissolved, thus promoting the disintegration of the rock. This action is greatly increased by various impurities which are frequently contained in the water, especially those derived from organic decay. The action of gases in volcanic regions may be classed as a chemical process of weathering. The rapidity with which rocks disintegrate under the chemical processes of weathering depends mainly upon the composition of the rock, the composition and quantity of the water and the temperature. Under the mechanical processes of weathering may be classed the impact of falling rain, the wedging action occasioned by water freezing within the interstices of the rock, the

wedging action caused by the roots of plants entering the crevices of the rock, and the variations in temperature, particularly rapid changes in temperature. In regions where the soil covering is derived from the native underlying rocks, the soil is entirely due to the effects of weathering, and the amount of such soil represents the rate at which weathering outdistances the rate of soil removal by transportation. The processes of weathering are largely responsible for the width of stream valleys, for by these agencies the rock is broken up and loosened

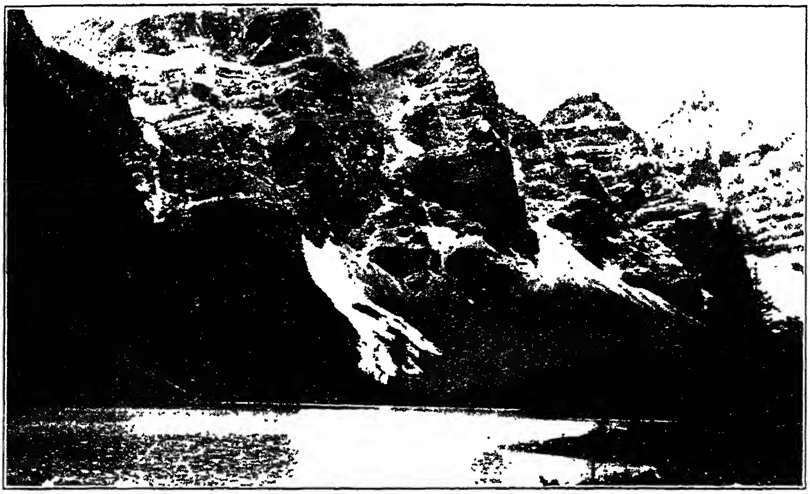


Fig. 172.—Talus at the Base of Mountains around Moraine Lake, British Columbia.

from the sides of the hills and canyons, whence it falls to the stream by which it is broken up and carried away.

The deep soil, which is the result of weathering when soil removal has not hitherto been active, is shown by Fig. 9, page 39. Fig. 172, shows the talus at the base of the mountains surrounding Moraine Lake in British Columbia. This lake is of glacial origin and the talus represents the effects of weathering since the time when the valley was occupied by the glacier.

150. **Corrasion.**—Corrasion is due in large measure to the abrasive action of material carried in suspension in running waters, and the larger part of this suspended matter is composed of material broken up and loosened by the processes of weathering. When the water of a stream runs over a bed of rock, the destructive effect is dependent upon the velocity of flow, the depth of flow, the load of detritus it car-

ries, and the character of the rock; in other words, the amount of work accomplished depends upon the material worked, the tools used and the energy expended. The principal work is accomplished by the boulders which are rolled along the stream bed (see Fig. 173), and since the size of the boulder moved by a stream varies as

FIG. 173.—Tools of the Stream, Boulders in the Spokane River.

the sixth power of the velocity, the velocity is the important factor in influencing the rate of cutting. That a stream normally swift may be so loaded with detritus that its velocity is materially diminished, may readily be seen when it is considered that it is the bottom velocity and not the average velocity which is effective in cutting, and each addition to its load reduces the energy of the flowing water by the amount necessary to carry the weight along. The maximum rate of corrasion therefore occurs when there is that balance beween velocity and load carried that permits of the most effective abrasive action by the debris upon the stream bed. In those regions where the large part of the yearly precipitation occurs as snowfall, and the summer temperatures are not sufficient to melt all the snow which fell in the previous season, the greater part of corrasion and transportation is accomplished by the movement of glaciers.

151. Erosion By Wave Action.—The nature of waves and the tremendous force of their impact have already been discussed in Sec-

tions 55 to 60 inclusive. When waves beat against a shore, especially when they are loaded with debris, they may cause considerable erosion, depending on the nature of the material of the land, the beach struc-

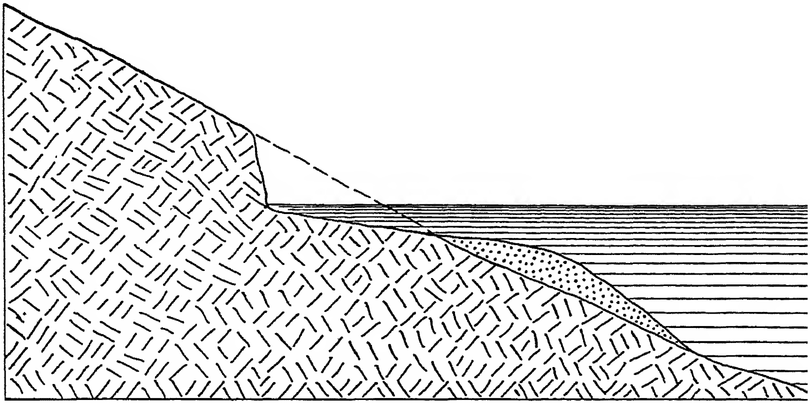


Fig. 174.—Coast Erosion by Waves.

Fig. 175.—The Illecellewaet Glacier, British Columbia.

ture, and the depth of water adjacent to the shore. The normal effect of the waves is both to cut a terrace in the shore line and by means of the receding waters to build up a terrace in the adjacent deep waters. (See Fig. 174). While the material eroded from the shore may furnish effective tools to assist corrasive action of the waves, unless it is largely removed, either by falling into deep water or by cur-

rents, from those sections where erosion is in progress, it soon forms a protective covering and prevents further effective wave action.

152. **Glacial Erosion.**—In the high mountains and in the poleward regions beyond the snow line where the summer heat is insufficient to melt the winter snows, snow fields are formed which by the accumulated pressure due to their great depths convert their lower portions into ice and force streams of ice slowly down the valleys (see Fig. 175), until the end of the glaciers reaches a region where the summer temperatures are sufficient to limit the glacial movement. (See

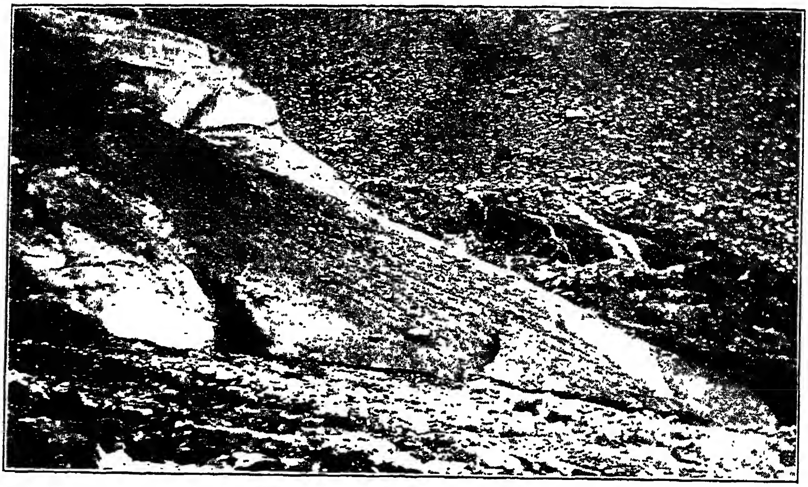


FIG. 176.—End of the Great Glacier, British Columbia.

Fig. 176). The effect of these slowly moving masses of ice may easily be imagined. They grind down the valley bottoms and sides and often shove before them or carry within their structure or on their surface the materials which they have eroded or which through other causes have become disintegrated or broken from the valley structures and become imbedded in or deposited on the glaciers. This material is slowly moved forward and is finally deposited at the end or side of the glacier where the ice within or upon which it is transported is melted by the temperatures of the valleys which limit its advance.

When the end of the glacier remains in one position for a long period and its movement is continually depositing material at its terminus as the ice melts, it builds up deposits which vary from low ridges to considerable hills and are called *terminal moraines.* Such deposits fre-

quently dam the waters of a valley from which the glacier has withdrawn and create lakes as in the case of the moraine below Moraine Lake in the valley of the Ten Peaks in British Columbia. (Fig. 177). When the glacier is retiring, due to increased temperature or decreased precipitation, no moraine marks its terminus unless it becomes stationary at certain points for considerable periods, but the material carried is distributed over the bed which it formerly occupied.

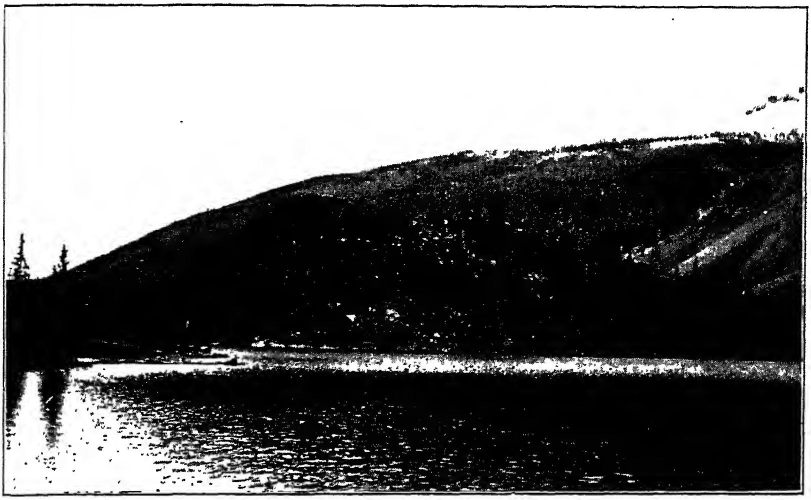


Fig. 177.—Terminal Moraine at the Outlet of Moraine Lake British Columbia.

(Fig. 176.) Often much of the finer material is carried away by the glacial waters which result from melting. In other cases the glacier reaches the ocean before melting and breaks off in icebergs which float away, carrying with them the materials contained in their mass. (See Fig. 178, page 318). While glacial action is of comparatively little importance at the present time in the United States, such work is still in progress in the mountains of the northwest, and most of Greenland and much of the polar regions are covered with perpetual ice. Much of the United States and of the northern portion of Europe and Asia have been greatly modified by such action during periods when glacial conditions were much more extended than at present.

153. **Movements of the Earth's Crust.**—There are in general four ways by which the surface materials of the earth change their positions:

First—By displacement or diastrophism when the crust of the earth is upheaved or depressed.

Second—By avalanches or landslides where unstable masses of rock slide into adjacent depressions.

Third—By volcanic action or vulcanism when the earth's crust is rent and molten material is ejected.

Fourth—By transportation when the material of the crust is broken, crushed, disintegrated and moved by the winds and waters from one region to another.

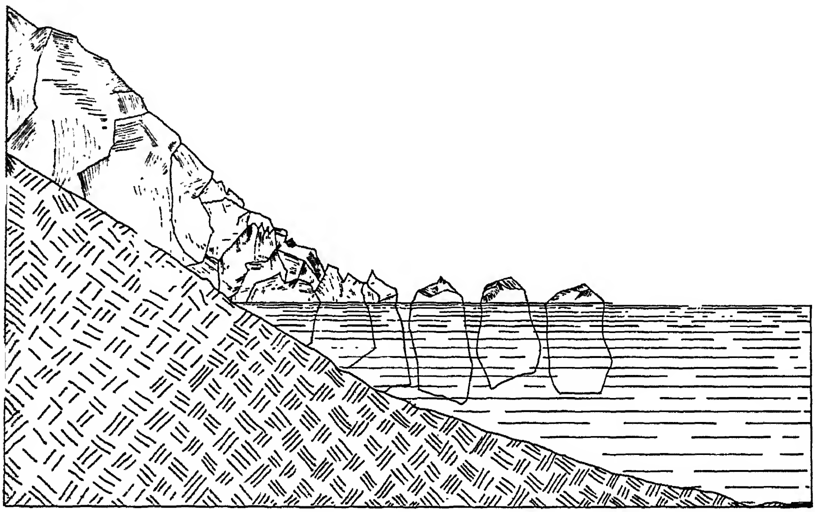


Fig. 178.—Formation of Icebergs (see page 317).

Diastrophism—The crust of the earth in many places rises and sinks but this action takes place so slowly that in few cases can the changes be perceived except by comparison during long intervals of time.

If the crust of the earth were uniform in elevation, the entire surface would be covered by water to an approximate depth of two miles. It is this diastrophic movement of the crust which has produced an unequal surface and has given rise to the continents and islands. These land masses have changed and still are slowly changing their forms and extent as the surfaces rise, sink or perhaps remain stationary for a period of time.

The main continent forming movements appear to have occurred prior to the formation of the earliest known sedimentary rocks.[1] There have been times in past geological ages when great lateral thrust has occurred, perhaps through the cooling and shrinking of the

[1] See Chamberlain and Salisbury Geology, Vol. 1, p. 519.

earth's interior, and the surface strata have been warped and folded into mountain chains. This has usually occurred near the continental borders. The resulting folds are sometimes upright and symmetrical but more often inclined and unsymmetrical, and the strata are so warped, twisted and faulted as to make the age of the strata in a given vertical section not always in accord with their positions. In other cases, great plateaus have been raised high above the oceans and more or less flexed, tilted and faulted but forming together vast high and more or less level plains in which erosion has had comparatively little effect in altering the main surface contours. These movements while still taking place are so slow that they have little effect in engineering works except that a knowledge of the conditions which have obtained in the past frequently furnishes a basis for understanding the conditions which may be expected in carrying out such works.

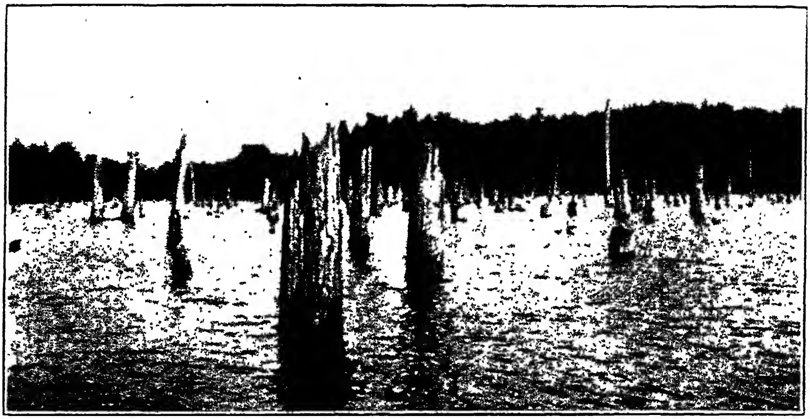


FIG. 179.—Dead Forest in Reelfoot Lake, Tennessee.[3]

There have been times, as in the case of earthquakes, when crust movements have been immediately apparent and when fissures were formed in the crust, and one side has dropped and the other has been uplifted, either or both of which has occurred at the same period. In an earthquake that occurred in Japan in October, 1871, there was a vertical displacement of from two to twenty feet that could be traced for forty-six miles, and a horizontal displacement at one point of as much as thirteen feet.[2] Sometimes such movements interfere with the movements of ground water, new springs are formed and old ones cease to flow, and occasionally ponds and lakes are formed.

[2] Chamberlain and Salisbury Geology, Vol. 1, p. 510.

In the earthquakes of 1811 and 1812 great depressions occurred near the Mississippi River in Kentucky, Tennessee, Missouri and Arkansas, and those areas became marshes and permanent lakes, in some of which standing trees are still visible. (See Fig. 179.)[3]

One of the most disastrous earthquakes of modern times occurred near San Francisco in 1906. This was caused by a new slipping on the old fault plane which has been traced for a distance of about 180 miles. (See Fig. 180.) The horizontal displacement shown by the existing

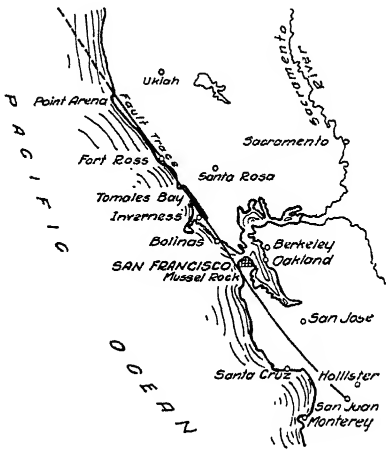


Fig. 180.—Fault Line of the San Francisco Earthquake of 1906.

roads, fences, etc. (see Fig. 181), was considerable. Many buildings and engineering works, pavements, pipe lines, etc., were destroyed by the shock, but the principal losses were caused by the resulting serious conflagration which destroyed most of the City of San Francisco.[4]

These disturbances are of great importance to the engineer who may have hydraulic works to construct in countries where earthquakes are liable to occur. Such structures must be carefully designed with such occurrences in view both for the safety of the structures and of the lives of the people which may depend upon such safety.

Landslides—Masses of earth and rock on unstable slopes sometimes break away and slide into adjacent depressions. Conditions favorable to such occurrences exist where the masses overlie or consist largely of beds of soft incoherent material and especially where the bed joints are inclined toward the surface and the mass above has vertical jointing.

[3] The New Madrid Earthquake, by M. L. Fuller.

[4] The San Francisco Earthquake, by G. K. Gilbert, et al.

The undercutting of streams and the saturation of the strata are factors which commonly make gravity effective in natural slides.

In engineering works similar slides are caused by the weakening of strata by excavation for canals and railroad cuts or in mining and other works where masses of materials are removed from their natural beds. Such slides also occur in earth dams, reservoir embankments and levees where poor materials, improper construction or too great surface slopes are employed.

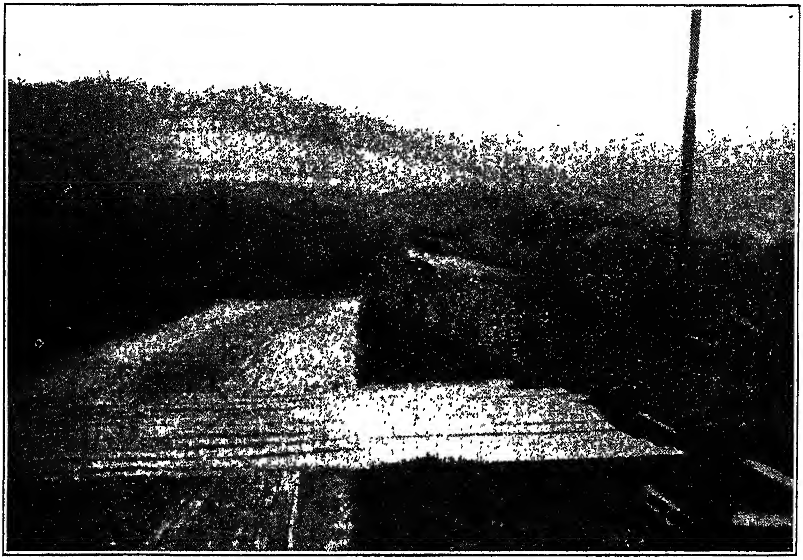


FIG. 181.—Horizontal Displacement During the San Francisco Earthquake shown by Road and Fence Line (see page 320).[4]

Vulcanism—Occasionally the crust has been rent by shocks, and molten matter is then sometimes ejected, pouring out in great streams of lava which spread over the surface and form extensive deposits. Such action at the present time has been extremely local in extent and outside of limited localities is of little importance to the engineer.

Transportation—The runoff of the rainfall washes the sands and finer material from the mountains, hills and plains into the streams by which it is carried away and deposited on the lowlands, in the river channels or in the lakes and oceans where it is distributed by the currents and waves and builds bars or forms new lands adjacent to the shores.

Transportation of material may occur in several ways. The fine fragmentary particles of the rock may be carried in suspension in the waters of the stream and the coarser portions may be rolled and pushed along the bed of the stream by the action of the current. Frequently the amount of the coarser materials that are moved along the bottom of the channel is very great. The amount of material so transported is dependent upon the velocity of the stream and its depth, together with the accessibility of material that can be carried.

FIG. 182.—Deposits of Sand and Gravel behind the Danville Dam.

Figure 182, shows the amount of material which had accumulated behind the dam at Danville, Illinois, in about a year after its construction. The dam built across the north fork of the Vermillion River was about thirteen feet in height and the stream which was of a somewhat flashy nature, during its rapid rises, not only carried a large amount of silt in suspension but also rolled along its bed large quantities of gravel and coarse sand which was stopped by the dam and accumulated until its top approached so near to the top of the dam that the velocity of the stream was sufficient to raise it over the crest. Hundreds of yards were deposited in this way, reducing the value of the storage pond which was formed by the dam. In this case the storage basin above the dam was not sufficient to prevent considerable current in time of flood and little or no silt was deposited except during very low floods.

Large boulders and other debris from the disintegration of the rock masses may fall or slide from the valley sides and find lodgment upon the river ice, or the ice may freeze to boulders along the bottom and shores of a stream, and upon breaking up in the spring, may transport them considerable distances. In the same way material is re-

TABLE 36.

Matter Carried in Solution and Suspension by Various River Waters of the United States.

Stream	Location	Parts per million In solution	Parts per million In suspension
Arkansas	Kittanning, Pa.	82	100
Allegheny	Little Rock, Ark.	630	748
Big Vermillion	Danville, Ill.	281	82
Brazos	Waco, Texas	1,136	488
Cedar	Cedar Rapids, Iowa	228	61
Chippewa	Eau Claire, Wis.	90	4
Colorado	Austin, Texas	321	351
Cumberland	Nashville, Tenn.	119	94
Fox	Ottawa, Ill.	335	87
Hudson	Hudson, New York	108	16
Illinois	LaSalle, Ill.	278	136
Kentucky	Frankfort, Ky.	104	142
Mississippi	Dayton, Ohio	289	94
Mississippi	Minneapolis, Minn.	200	8
Mississippi	Quincy, Ill.	203	119
Missouri	Memphis, Tenn.	202	519
North Platte	Florence, Nebr.	454	2,059
Ocmulgee	No. Platte, Nebr.	295	311
Potomac	Macon, Ga.	69	174
Red	Cumberland, Md.	130	29
St. Lawrence	Shreveport, La.	561	870
Savannah	Ogdensburg, N. Y.	134	T.
Susquehanna	Augusta, Ga.	60	142
Tennessee	Danville, Pa.	112	21
Wabash	Knoxville, Tenn.	112	156
Tennessee	Logansport, Ind.	807	117

ceived and transported by glaciers. The great glaciers of past ages had an exceedingly great influence upon the topography of the regions which they covered, by their transportation of vast amounts of material.

The wind in certain regions of the globe is an important agent in the transportation of sand and dust. Examples of the action of wind in its effect upon the topography may be seen in the great shifting sand dunes of the Carolinas and Michigan, and in a number of places in the arid portions of the United States and other countries.

The transportation as effected by stream flow may cause either degradation or aggradation, depending upon whether the stream is picking up and carrying its load of detritus or because of reducing velocity or

volume is unable to carry the load farther, and deposits it, thus building up its bed.

The average amounts of matter in solution and in suspension in parts per million carried by various rivers of the United States as determined during the years 1906–07 were as shown in Table 36.[5]

154. **Results of Erosion.**—Table 37 shows the estimate of C. C. Babb[6] of the average amount of sediment carried in suspension by large rivers of the world to which has been added in the last column the number of years required to reduce the drainage area one foot at the rate given.

In the process of erosion lakes are but temporary features; in the lapse of time, their outlets become so lowered that they are drained,

TABLE 37.

Discharge and Sediment of Large Rivers.

River	Drainage area sq. miles	Mean annual discharge sec. ft.	Total annual tons	Sediment Ratio by weight	Depth over drainage area in.	Years required to reduce area 1 ft.
Potomac	11,043	20,160	5,557,250	1:3575	.00433	2,774
Mississippi ..	1,214,000	610,000	406,250,000	1:1500	.00288	4,170
Rio Grande...	30,000	1,700	3,380,000	1:291	.00110	10,900
Uruguay	150,000	150,000	14,782,500	1:10,000	.00085	14,100
Rhone	34,800	65,850	36,000,000	1:1775	.01071	1,120
Po	27,100	62,500	67,000,000	1:900	.01139	1,052
Danube	320,300	315,200	108,000,000	1:2880	.00354	3,390
Nile	1,100,000	113,000	54,000,000	1:2050	.00042	28,600
Irrawaddy ..	125,000	475,000	291,430,000	1:1610	.02005	600

and the material carried by the waters of the rivers eventually reaches the sea.

The waves of the lakes and the oceans as they beat against the shores erode the cliffs and spread the coarser material along their margins (see Fig. 174, p. 315) which in turn is worn by wave action and transported by the waves, currents and tides and formed into new deposits.

The ultimate results of unchecked erosion would be to reduce the land surface nearly to sea level. Gradually and more and more slowly as the gradient is decreased by erosion, the topographical features of the land are reduced and the process would result in a featureless peneplain or base level with just sufficient gradient to discharge the rain waters into the sea. These ultimate results from erosion on the land areas during the past geological ages have never been more than ap-

[5] Water Supply and Irrigation Paper No. 236. The Quality of Surface Water in the United States, R. B. Dole.

[6] Science, 1893; Vol. XXI, p. 343; also Eng. News, 1893, p. 109.

proximated as the conditions of erosion have ever been modified, accentuated or destroyed by diastrophic movements, upheavals or depressions of the earth's crust which have either raised the land areas more or less and given greater opportunities for further erosion or have sunk them nearer or below the sea level where new deposits were perhaps laid down over them, obliterating such previous erosive effects as may have remained.

155. **Origin and Development of Drainage Valleys.**—Wherever land surfaces have appeared above the sea, drainage systems have soon been established. The original drainage lines have either followed natural depressions in the crust or depressions that have resulted from lines of structural weakness where normal erosion has been comparatively rapid.

Extensions of the systems of drainage have resulted from further erosion which must normally proceed most rapidly along lines of weakness caused by weak strata or by other causes which have reduced resistance and increased erosion, and which proceed slowly when the strata are resistant and when other causes of erosion are retarded. In this way the original drainage development of a country may, with the passage of time, be radically changed and areas drained by one stream in which erosion has been held in check, may be seized by the tributaries of a different stream where erosion is more rapid.

In the same manner the tributaries of a main stream are pushed farther and farther toward the divide and frequently even into lands beyond, until a complete system of drainage may effectively be provided for thousands of square miles of territory. Such systems have been frequently altered and changed by diastrophism, vulcanism and glaciaion. At any one time the larger streams are the result of ages of erosion and geological change and represent within their length, all stages in river growth.

Where the strata in which a stream develops have approximately uniform resistance, a normal stream bed having a concave profile is developed. (Fig. 183). The gradient of the lower portion on account of its age and larger flow, has reached a less inclination at or approximating its base level. The middle course being younger has a higher gradient and a considerable flow, and here maximum corrasion usually occurs. The upper portion being of more recent origin and with a small amount of flow except at times of flood, has a high gradient.

Streams with high gradients and consequent high velocities are able to transport considerable amounts of sand and heavier rock material

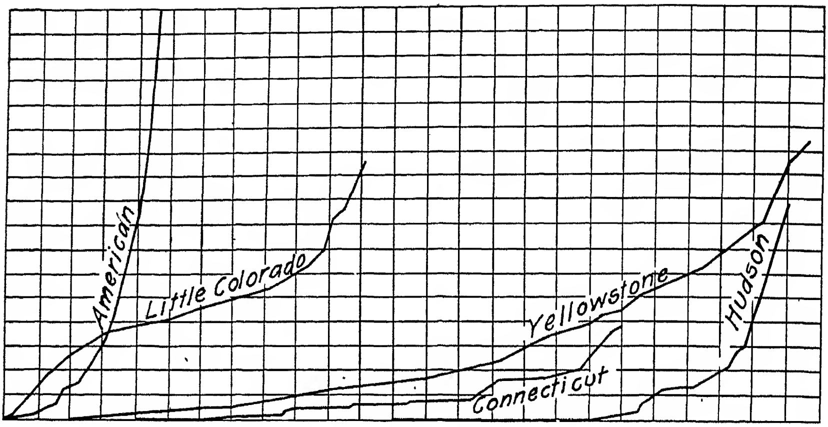


FIG. 183.—Stream Profiles.

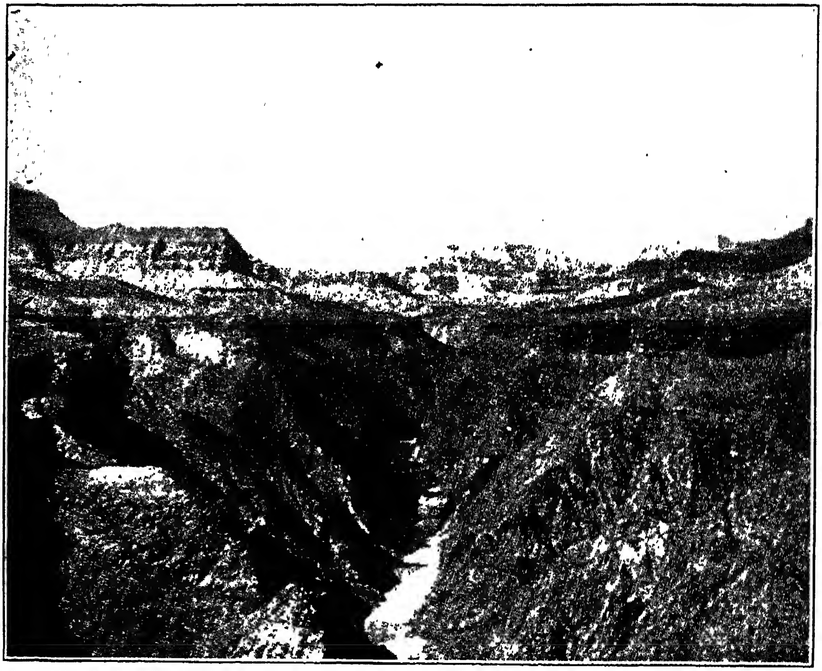


FIG. 184.—Vertical Erosion of the Colorado River.

which corrade their beds and result in comparatively rapid vertical and small horizontal erosion. (See Fig. 184.) The work of streams with low gradients is largely confined to working over the material in their

beds and banks. During periods of floods the excess energy in their waters excavate their channels (see Fig. 185) and destroy or rearrange their banks (see Fig. 186), and frequently rearrange their local channels. (See Figs. 202 and 203, page 340.) With the subsidence of the flood stage large amounts of sediment are deposited, old channels are filled and excavations in their beds are restored. The study of the work of streams is highly important in connection with the design of river conservancy and flood protection work.

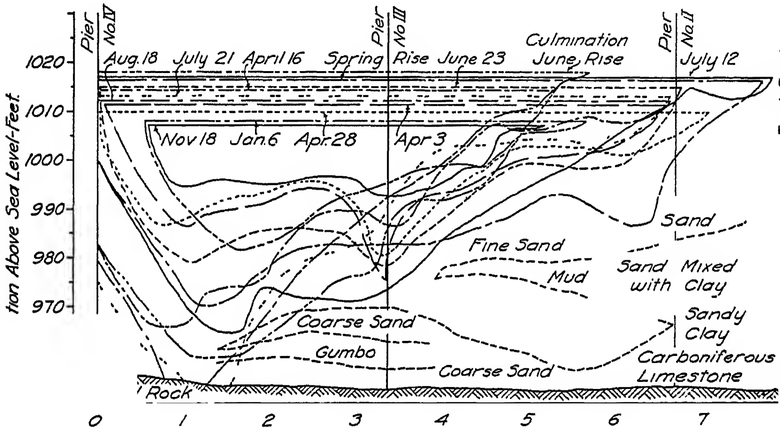


FIG. 185.—Variations in Cross Section of the Missouri River at Omaha.*

156. **Origin of Falls and Rapids.**—When, in the development of a river, strata are encountered that have comparatively higher resistance, corrasion at such points becomes slow and falls or rapids result. A pool is soon formed below the resistant strata as the water with its sediment and the matter pushed along the bottom plunges over the resisting deposit onto the yielding strata below; and where the conditions are favorable, a permanent fall results. In such cases the normal concave profile will be modified locally to a greater or less extent. (See profile of the Little Colorado River.) In most cases, the ordinary inequalities in the strata of the stream bed create a condition of alternate pools and rapids which, however, often become comparatively insignificant and are more or less obscured when the flow is considerable.

The resisting strata which produce a falls or rapids may be a local inequality of limited extent, such as concretions or boulders, or it may be interbeded strata of high resistance. (Fig. 187, A and B, page 329.) Falls and rapids may result from an intrusive strata such as a dike of

*J. E. Todd, Bulletin 158, U. S. Geol. Survey.

resistant material which crosses the stream bed (Fig. 187 D) or where more or less horizontal strata of high resistant quality are inclined in the direction of or opposed to the flow of the stream. (Fig. 187 C).

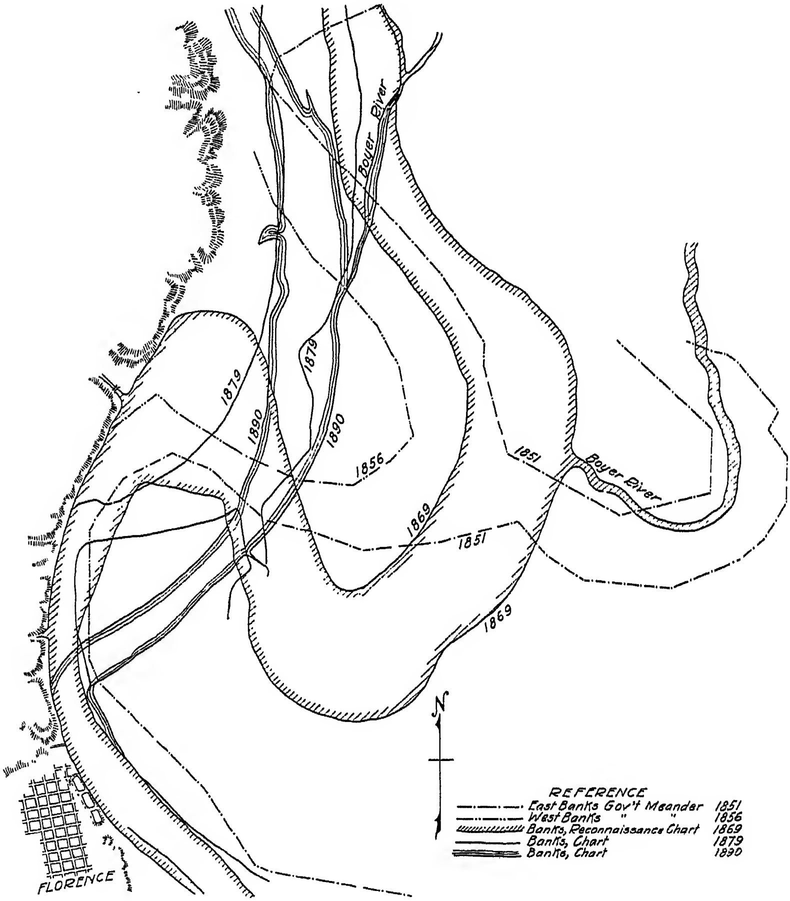


FIG. 186.—Shifting Channel of the Missouri River near Florence, Nebraska (see page 187).

Fig. 188, page 329, shows an intrusive dike across the Kicking Horse River near Field, British Columbia, which formerly created a fall at that point. The water has at the present time worn a way through the dike (see Fig. 189) and the fall is just behind it. The dike is now known as a natural bridge.

Yielding strata below the resistant rock are more rapidly eroded

while strata above the obstruction are in some degree protected by the lesser gradient that obtains above the fall. In any event, gradual degradation will occur at the crest of the fall which will slowly retire

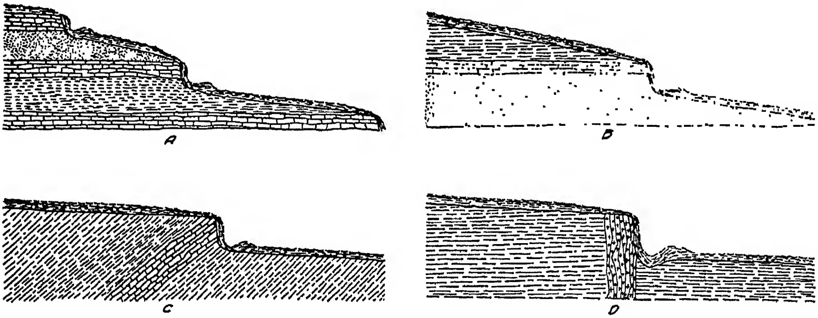


Fig. 187.—Falls and Rapids.

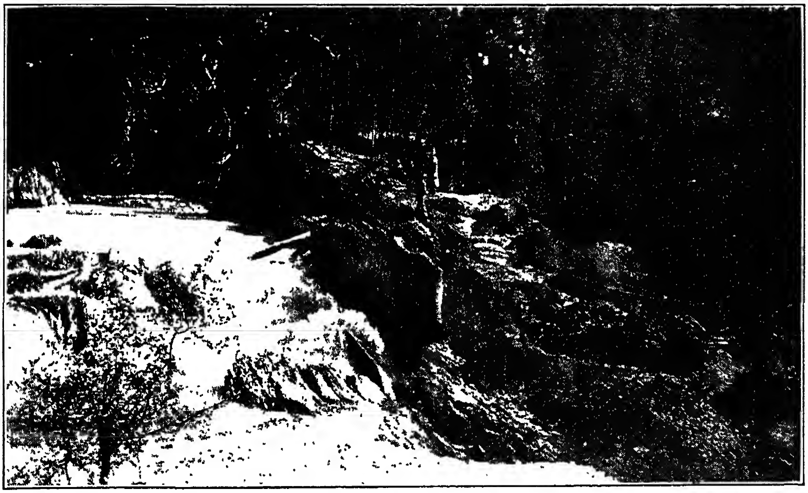


Fig. 188.—Intrusive Dike across Kicking Horse River, British Columbia (see page 328).

upstream as the resistant rock yields to corrasion. Sometimes the resistant rock is a comparatively thin deposit underlaid by yielding strata, as in the case of the Falls of Niagara.[7] (Fig. 190 A and B.)

In such cases the underlying yielding rock may be eroded by the corrasion of the waters or disintegrated by weathering, leaving the superimposed resistant strata overhanging and supported only by its transverse

[7] Rate of Recession of Niagara Falls, G. K. Gilbert. Bul. 306, U. S. G. S.

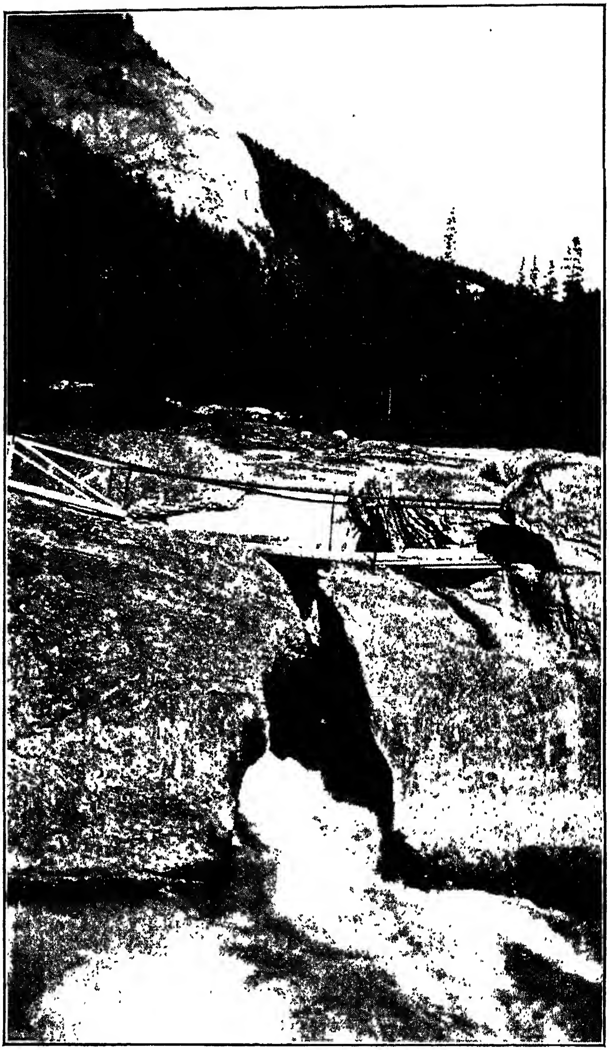


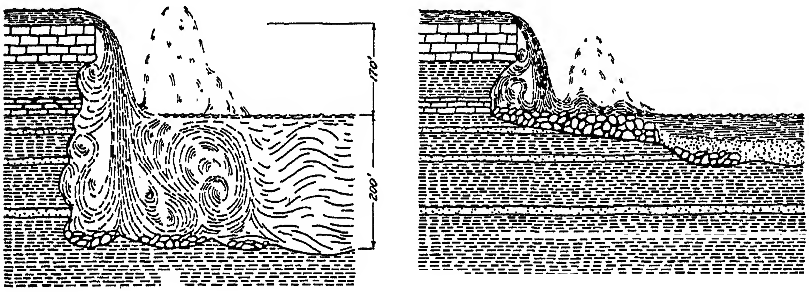
FIG. 189.—Natural Bridge on Kicking Horse River, British Columbia.

strength. When the unsupported weight is sufficient, the stratum is fractured and falls, and the crest of the fall recedes upstream. (See Fig. 191, p. 332.)

Should the resistant strata run out and be worn through, the falls rapidly disappear. A rapids first results which is quickly degraded as the yielding rock erodes. This nearly occurred at St. Anthony's Falls

on the Mississippi River at Minneapolis where the limestone cap was almost totally eroded, in which case the underlying sandstone would have been exposed and the fall would have disappeared. It was only by considerable labor and expense that the remaining rock was protected and the fall thus artificially saved for water power purposes.

In glaciated areas the whole drainage topography has been modified and largely or entirely destroyed, a new topography has resulted, and numerous falls and rapids have been developed. In Wisconsin the preglacial valleys have been filled with clays, sands, gravels and boulders for 200 feet or more. On the recession of the glaciers a new drainage system began to develop and the country still presents the ap-



A B

FIG. 190.—Falls of Niagara (see page 329).

pearance of topographical youth. Even when the new streams partially occupy old valleys and flow over materials which are easily eroded, erosion is frequently held back by obstructions at the outlets. The lower Wisconsin River, for example, flows over a yielding deposit 200 feet or more in thickness, but the river at its lower end has reached its base level on account of the obstruction by the gradient of the Missisipi River.

In many places, these new streams in rapidly eroding their channels through the yielding drift material, have encountered rock. At such points erosion is delayed, while it rapidly proceeds in the stretch below the ledge. The result is the development of falls like those on the Peshtigo River at High Falls (see frontispiece, upper figure), where a drop of over forty feet has been formed. This drop with the smaller falls and rapids above, permitted a hydraulic development of over eighty feet at this point. (See frontispiece, lower figure.)

The development of a fall or rock rapids in glaciated country indicates that the stream bed is not over the thalwag of the preglacial stream and is an indication that the lowest outlet past the ledge has not been

uncovered by the modern stream. Sometimes the rock outcrop occurs where the stream has turned through a gap in preglacial hills and the channel is then safely protected from radical changes as in the case of the Rock River at Rockford, Illinois, where the original channel extends to the southward while the modern stream turns through a saddle in the hills to the southwest. The Mississippi River at Rock Island

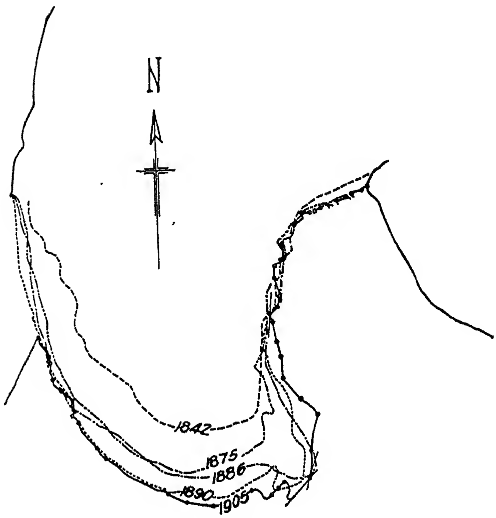


Fig. 191.—Recession of Horseshoe Fall (see page 330).

Limiting dates	Period years	Average annual recession from parallel ordinates	from areas
1842–1875	33	4.0	4.4
1875–1905	30	6.6	5.6
1842–1905	63	5.3	5.3

Rapids above Moline, Illinois, is also an example of such a change in course. Sometimes the rock outcrop which produces the falls is on an ancient hillside and in such cases a dangerous condition may result under which, with unusual floods the stream may radically change its course. Such a change took place in the flood of October, 1911, at Black River Falls, Wisconsin. (See Fig. 192.) A view of these falls before and after the flood is shown in Fig. 193, page 334. The Black River at this point flows over a rock out-crop on a preglacial hillside. A dam had been built at this falls, the north end of which abutted against glacial drift which was not properly protected. The flood waters rising over the abutment readily cut away the drift material and the river turned around the end of the dam into the

lower portion of the city, destroying many buildings and much property. (See Fig. 194, page 335). When the river was turned back into its course by the construction of a diverting and retaining wall across its new channel, the surface of the rock under this wall was found to be fifty feet below the rock of the dam site.

Even in a glacial drift, the boulder clay is so resistant that the smaller streams erode it with difficulty and occasionally excavate the clay around boulders so large that they cannot be transported by the stream. This may finally result in such a resistant mass of boulders that a considerable rapids may be developed. (See Fig. 195, page 335).

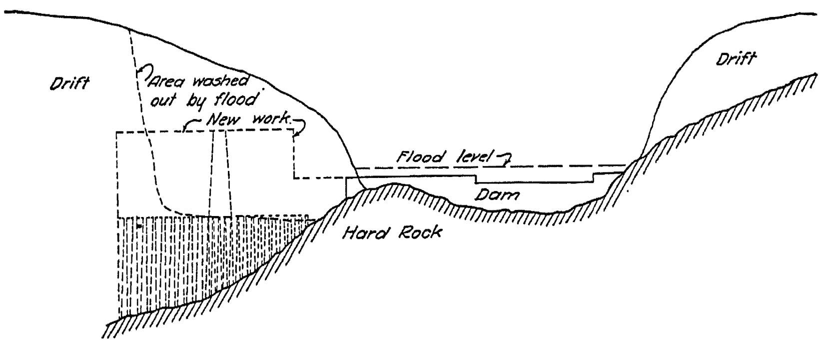


FIG. 192.—Rock Conditions at Black River Falls.

The water pouring over the brink of a fall develops considerable energy which is expended in impact and eddying in the waters below. Erosion is here materially augmented by the rocks, sand and gravel carried over the falls by the stream. The bed below a fall is therefore frequently excavated to a considerable depth below the stream surface. At the Horseshoe Falls of Niagara, the drop of the lower stream surface is about 170 feet, but the water below the fall is approximately 200 feet in depth, the bed being eroded in the softer material to this depth by the tremendous energy of the falling waters. (See Fig. 190A, page 331). The quantity of water which passes over the American side is not however sufficient to remove the fallen material from below. (See Fig. 190B.)

In the construction of dams the energy of the stream is frequently artificially concentrated in the same manner, and in such cases it is important to protect any yielding strata below the dam by a properly constructed apron or other protective work.

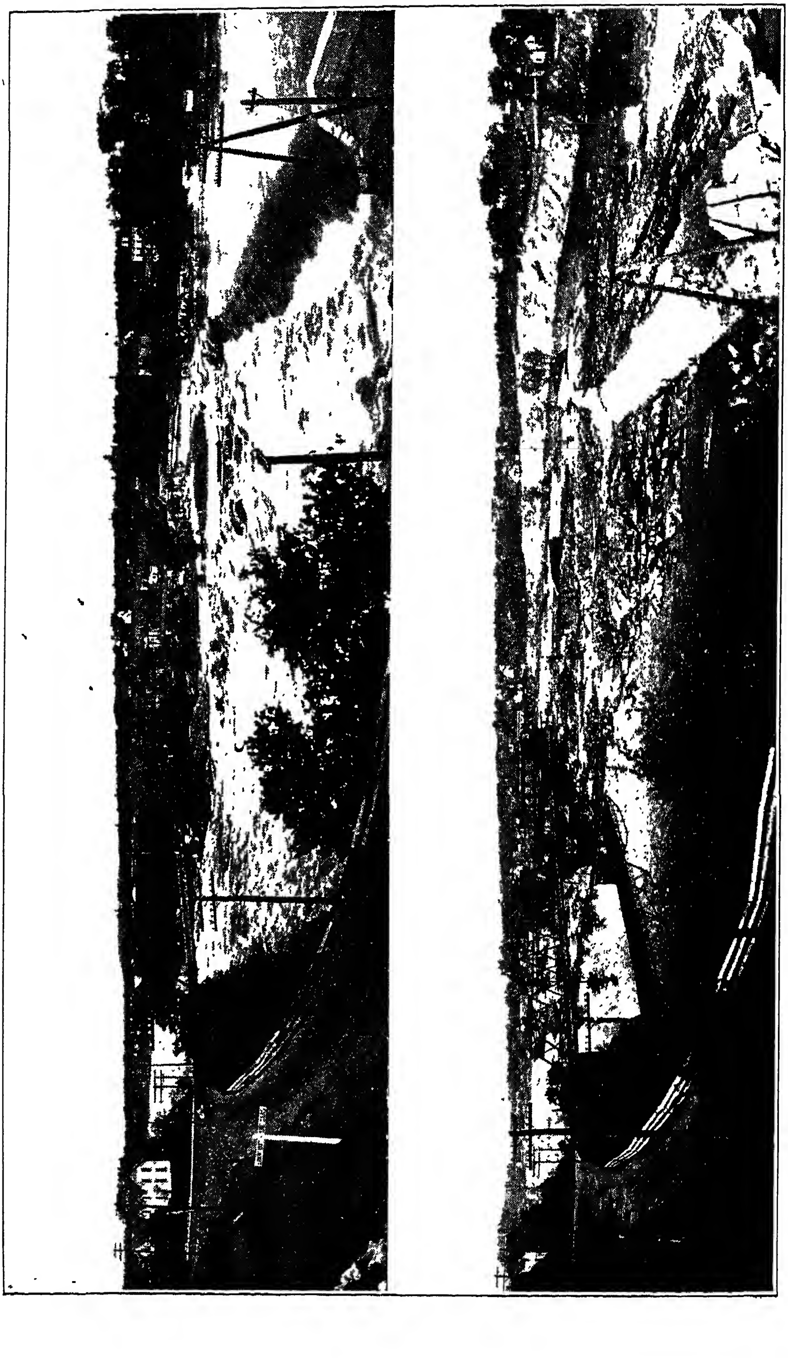


FIG. 193.—Black River Falls before and after Flood of 1911 (see page 332).

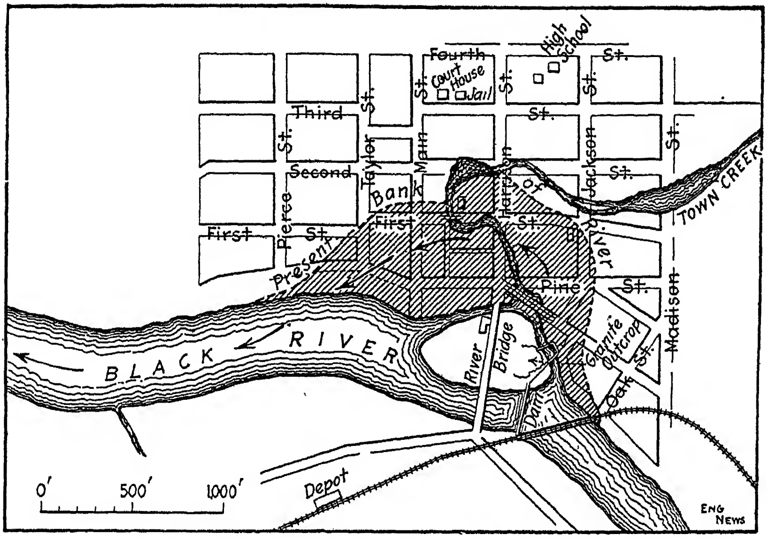


Fig. 194.—New Course of River at Black River Falls (see page 333).

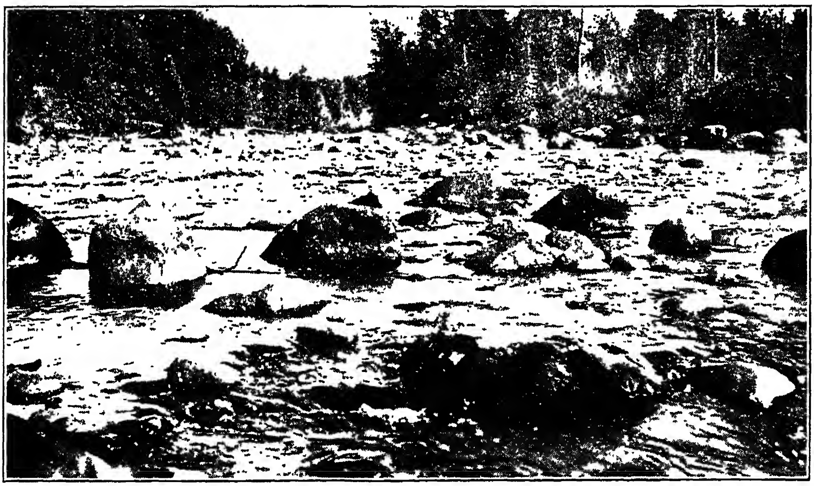


Fig. 195.—Boulder Bed of Wolf River (see page 333).

157. **The Origin of Lakes.**—Lakes are of various origins and may in general be classified in accordance with their origin as follows:

A. Diastrophic Lakes.—Caused by accumulations of surface water in the depressions which are due to displacement of the crust of the earth.

B. Crater Lakes.—Formed by accumulations of surface water in the craters of extinct volcanoes.

C. Glacial Lakes.—Formed in the topographical depressions carved by glacial action; caused by the obstruction of a valley by a terminal moraine or by the depression left by the melting of the glacier itself.
D. Bayou Lakes.—Occasioned by the cutting off and subsequent silting up of the extremities of a bend in a stream.
E. The damming of a water course by landslide or similar earth movement.
F. Obstructions formed across a river by deposition of material as a delta at the mouth of a tributary.
G. Basins due to chemical action such as solution of material to form a depression in limestone.
H. Basins excavated by the wind.

Inland lakes are subject to a further classification, depending in large measure upon the climate in which they occur. Observations show that with the proper topographic conditions a low rate of rainfall together with a relatively high rate of evaporation frequently results in lakes which can not rise sufficiently to overflow their basins, and the continued concentration of the mineral content of the water produces a salt lake. Ordinarily lakes that are provided with an overflow or outlet are composed of fresh water. The largest inland body of water on the globe, the Caspian Sea, is salt, while the second largest, Lake Superior, is fresh water.

The Great Lakes of North America are diastrophic in origin, although glacial action had much to do with their present form. It is probable that the valleys of these lakes were formerly drained by rivers forming a part of the preglacial St. Lawrence River system (Fig. 196, page 337). Later, during glacial times, a single lake probably occupied the valleys of Lakes Michigan, Huron, and Superior, and Lake Ontario was considerably extended. (Fig. 197, page 338). The lake system changed its form and outlet at various times during the glacial age. On the recession of the glaciers, this system was gradually drained, resulting in the system as it now exists.

A section along the Great Lakes is shown in Fig. 198, from which it will be seen that if the lake section was the result of the denudating effects of river drainage that disastrophism has since produced a reverse gradient in the valleys of the three upper lakes.

Crater lakes are comparatively few and only of local importance. The best example of these lakes in America is Crater Lake in Oregon which is over six miles in its greatest diameter and has a maximum depth of almost 2,000 feet. (See Fig. 199.)

Glacial lakes are very numerous within the glaciated boundaries of the United States. Thousands of these lakes are found within the terminal moraine in Wisconsin, Minnesota and other states. These

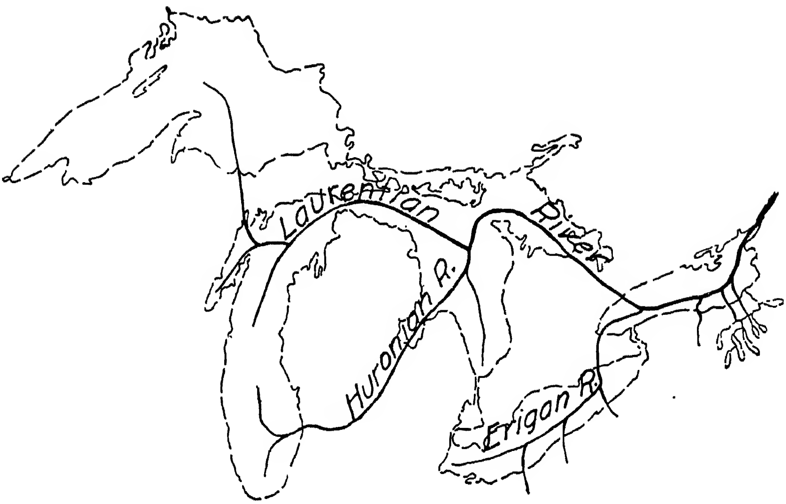


FIG. 196.—Preglacial St. Lawrence River Drainage (see page 336).

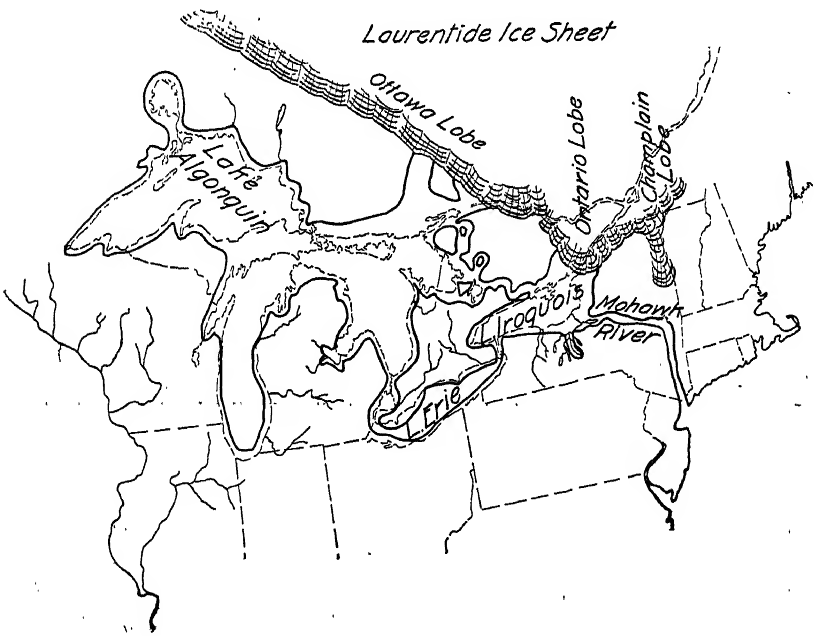


FIG. 197.—Glacial Lake Algonquin (see page 336).

lakes are frequently of importance as sources of water supply, sites for storage reservoirs and pleasure resorts. Some idea of their great number may be obtained from an examination of the map of the headwaters of the Wisconsin River. (See Fig. 200, page 339.)

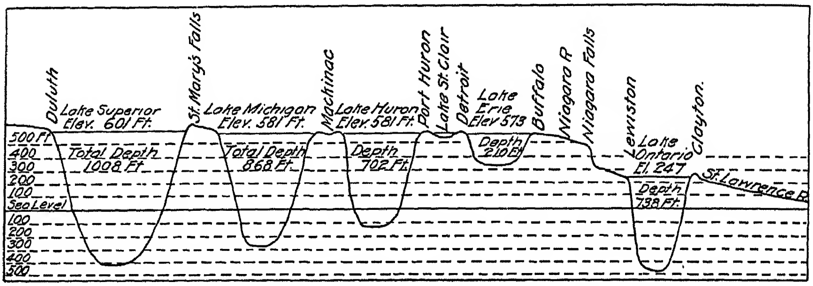


FIG. 198.—Section through the Great Lakes.

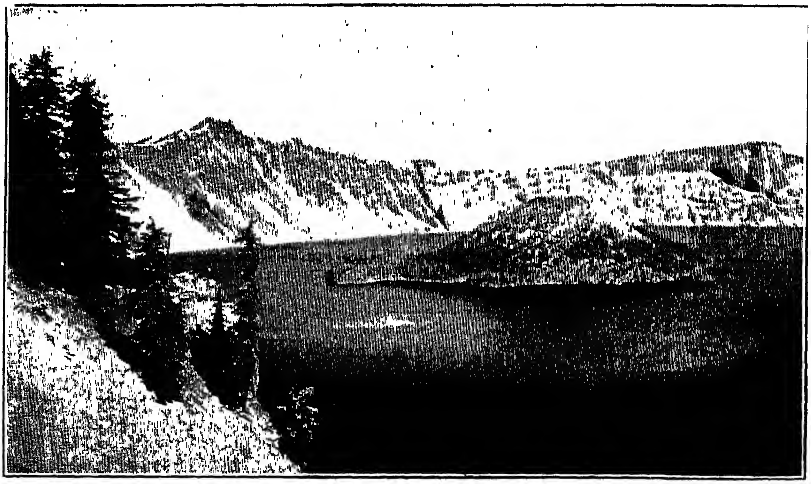


FIG. 199.—Crater Lake, Oregon (see page 336).

Lakes are sometimes formed in a stream valley by the building of obstructions to flow from the deposition of material brought to the stream by a tributary. Lape Pepin (see Fig. 201, page 339) on the Mississippi, formed by the deposits from the Chippewa River in Wisconsin, is an example of this action. The formation of this lake caused a retardation of the current of the Mississippi and a deposition of the materials conveyed by its waters when it entered the northern end of Lake Pepin, and resulted in a local delta formation and the formation of several minor lakes therein. This delta deposit has filled Lake

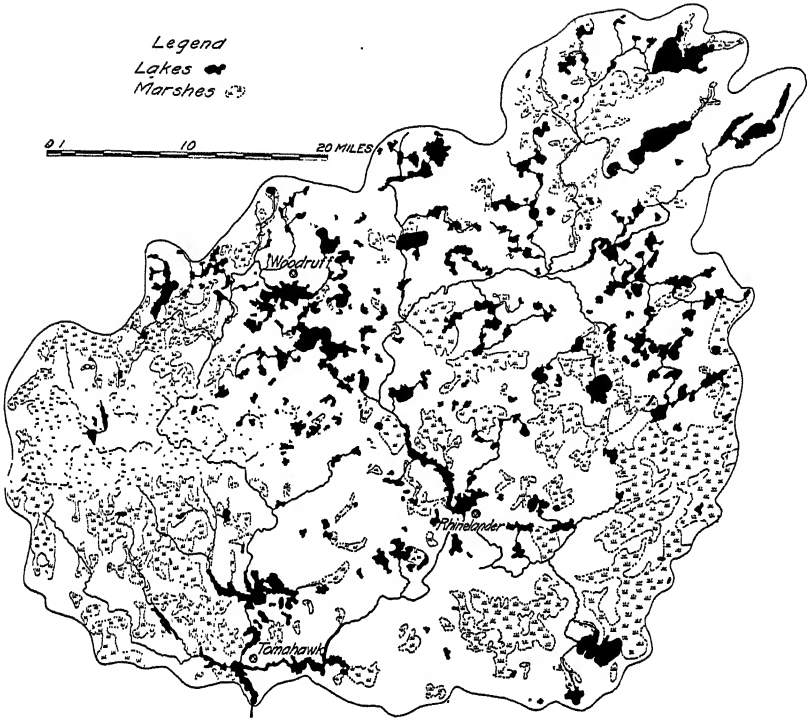


FIG. 200.—Intermoraine Lakes of Upper Wisconsin River Valley (see page 338).

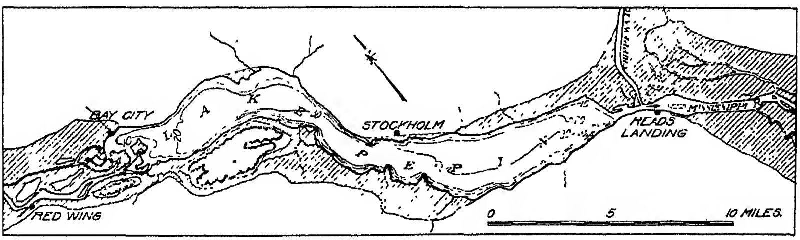


FIG. 201.—Lake Pepin (see page 338).

Pepin from a point near the mouth of the St. Croix River to which it probably extended at one time, to its present northern extremity near Bay City. The Mississippi by the deposits has dammed the outlet of the St. Croix to a depth of fifty feet or more, causing the formation of Lake St. Croix which is twenty-three miles in length and fifty feet or more in maximum depth.

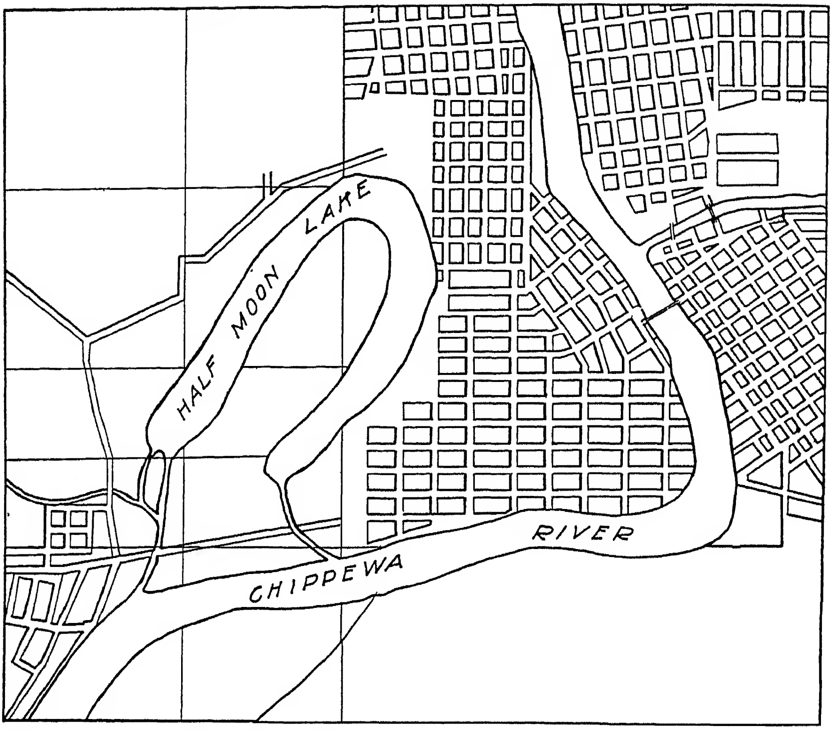


FIG. 202.—Lake at Eau Claire, Wisconsin (see page 341).

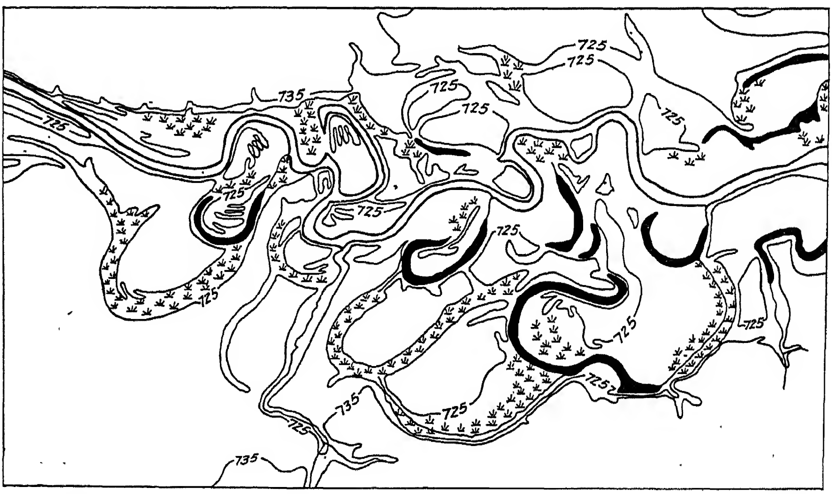


FIG. 203.—Bayou Lakes on the Pecatonica River, Illinois (see page 341).

Bayou lakes (see Figs. 202, page 340 and 203, page 340) and bayous still connected at their lower ends with the river are often found when both or only one of the extremities of a meander which has been cut off are filled by deposits. These are of common occurrence in regions of

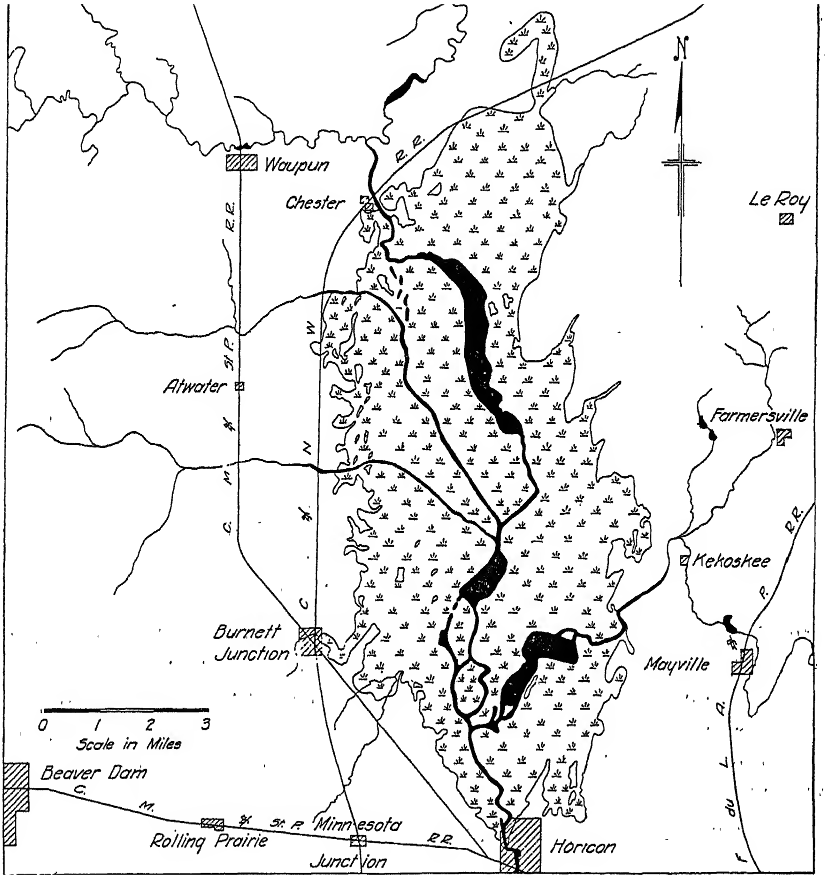


FIG. 204.—Example of a Silting Lake, Horicon Marsh, Wisconsin.

flat gradients and extensive flood plains. Lakes due to landslides and to chemical and wind action are of more limited occurrence and only of local importance.

158. Permanency of Lakes.—Ordinarily the lakes of a humid region are relatively short lived. The tributary streams bring in large amounts of sediment which are practically all deposited during the slow passage of the water through the lake, and the deposits of the re-

mains of plant and animal life all tend toward filling the lake bed. (Fig. 204).[8] The outlet stream has a continual cutting tendency to lower the elevation of the outlet, and thus drain the lake. This factor is usually of less importance than the sedimentation because of the fact that the outflowing stream usually contains little detritus and its eroding ability is correspondingly less. The result of these actions is to form an alluvial plain in the lake bed through which the stream pursues a sinuous course. When this condition is reached, the outgoing stream carries a considerable load of sediment and the

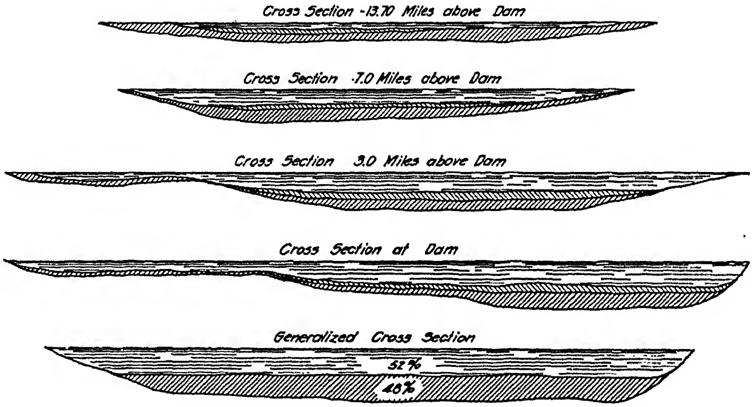


FIG. 205.—Silting of Lake McDonald, Austin Dam, Texas.

rate of corrasion is accordingly increased so that eventually all traces of the lake are removed by the lowering of the stream bed.

Sedimentation is continually going on in artificial lakes or reservoirs, constructed for the storage of water for irrigation, water power and other purposes; and where the material carried by the stream is considerable the reservoir may soon become silted up and useless.[9] By the construction of a dam across the Colorado River at Austin, Texas, a reservoir about nineteen miles in length was created. When the dam was completed in 1893, this reservoir had a capacity of 83.5 million cubic yards of water. In 1897 this capacity had been reduced 38 per cent by silting, and in 1900 the reduction was equal to 48 per cent of the original capacity (see Fig. 205).

Salt lakes of the arid regions commonly have longer existence than those of the humid regions, since sedimentation does not decrease the

[8] Physical Geography of Wisconsin, by Lawrence Martin.

[9] See Denudation and Erosion in the Southern Appalachian Region, by L. C. Glenn, Professional Paper No. 72, U. S. Geo. Survey.

volume of water except as the rise it causes exposes a greater area to the effects of evaporation. Traces of extinct lakes in the arid regions are more enduring than those situated in the humid regions, since the erosion and other weathering effected by the rainfall is not so rapid.

That fresh water lakes existed upon the face of the earth in remote geological ages is known by the deposits that were laid down and the fossil remains found in these deposits. Lakes more extensive than any

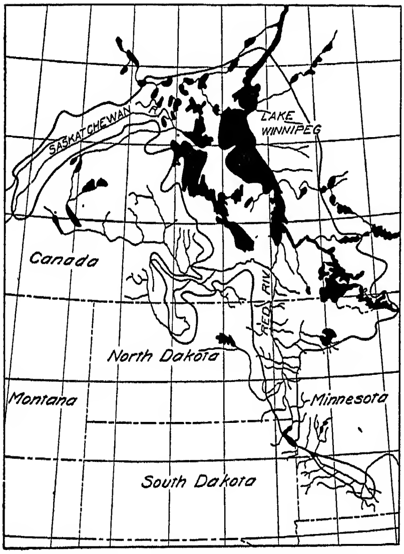


FIG. 206.—Glacial Lake Agassiz.

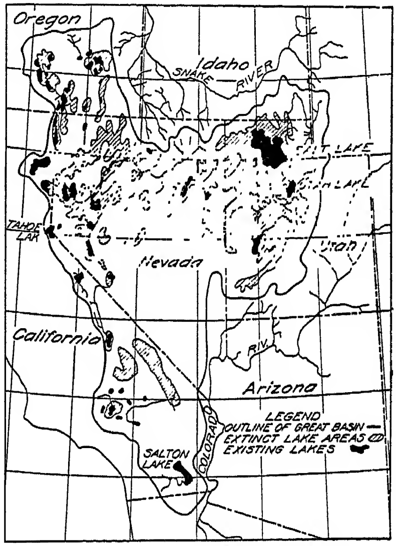


FIG. 207.—Lakes Bonneville and Lahontan.

now known probably existed in the Cordilleran regions. Sediments to the depth of several thousand feet were laid in some of them. Their bottoms have since been upheaved to form mountain ranges, and all traces of their shore lines have been obliterated.

Remains of fairly recent lakes in the United States are still quite discernible. Three of the largest and best known of these are Lake Agassiz, Lake Bonneville, and Lake Lahontan. Figures 206 and 207, are maps showing the outlines of these lakes so far as has been determined. Lake Agassiz is believed to have been formed by the great ice sheet which dammed the drainage of the Winnipeg basin and caused the waters to rise until a southward drainage was opened through glacial River Warren, about where the Minnesota River is located at present.

Lake Bonneville was situated on the east side of the Great Basin in the region where Great Salt Lake now lies. The waters from this basin overflowed northward through the Snake River into the Columbia. Its fluctuations are plainly marked by beaches upon the hills. (Fig. 208.)

Lake Lahontan occupied the western side of the Great Basin, and is at present represented by Pyramid, Winnemucca, Walker, Carson and Humboldt lakes in Nevada, and Honey Lake in California. This lake probably had no outlet. Its fluctuations are marked by great deposits of tufa composed principally of calcium carbonate. On favorable localities this deposit may be seen to be over eighty feet in thickness.

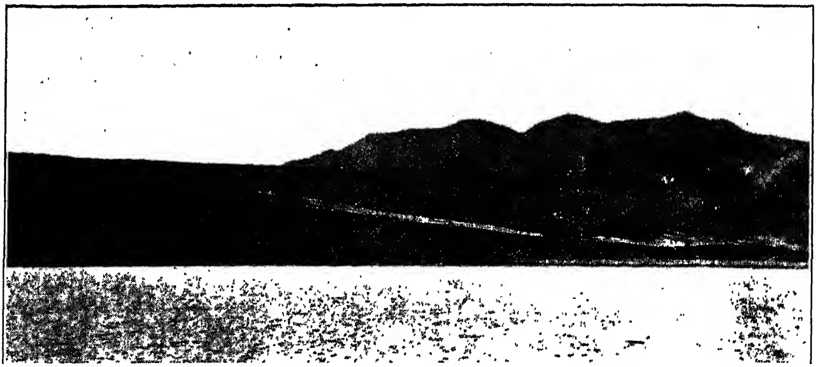


FIG. 208.—Terraces. Great Salt Lake.

159. **Changes in the Extent of Lands.**—The changes that have occurred and are now occurring in the limits of continental boundaries and the extent of the land surface are due to the factors already considered. Of these diastrophism, or the rising and sinking of the crust, is perhaps the most important. The change in the relative elevation of the sea level has also been an important factor. These changes have been caused not only by diastrophism but by the extension of the shores and the filling up of the lakes and seas by the materials resulting from the denudation of the land, and also perhaps during the glacial epoch by the extraction of large quantities of water from the ocean by evaporation and its storage as snow and ice in the great glaciers that have from time to time accumulated in polar regions and overrun considerable portions of the Northern and perhaps the Southern Hemisphere.

A former extension of the eastern coast at some time in the past is illustrated by Fig. 209, page 345, which shows the *continental shelf*

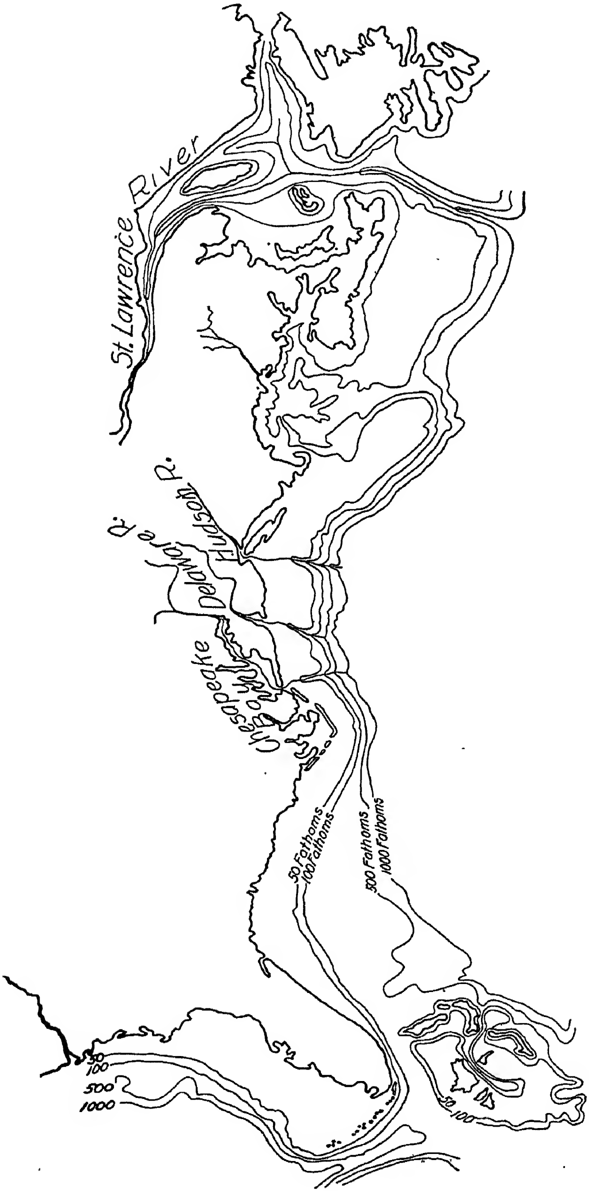


FIG. 209.—The Continental Shelf on the Atlantic Coast (see page 344).

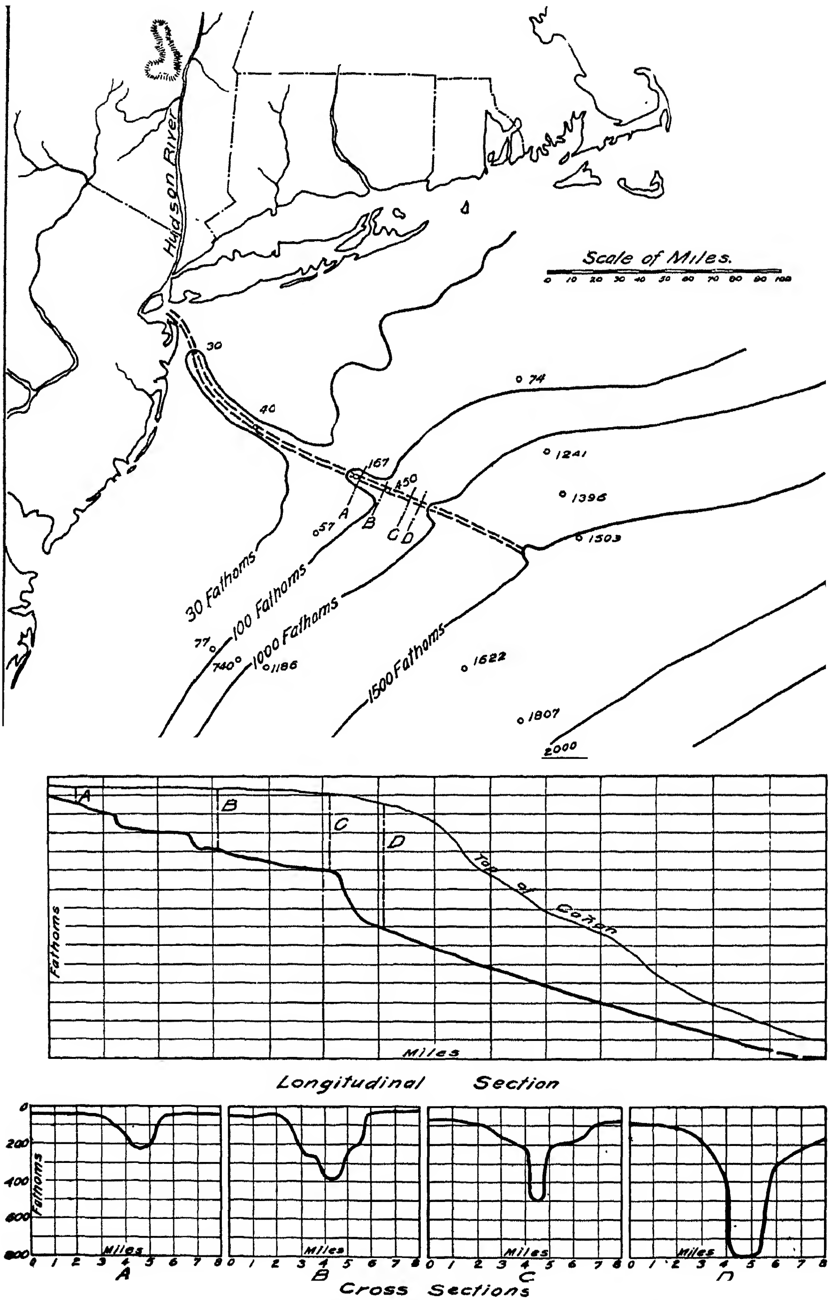


FIG. 210.—The Submerged Valley of the Hudson River (see page 347).

along the eastern United States, the limits of which mark the former boundary of the continent. Proof of this is furnished by the fact that many of the valleys of the eastern river systems can be traced to the edge of this shelf, and it is clear that these valleys could have been formed only by atmospheric and eroding agencies during the time that

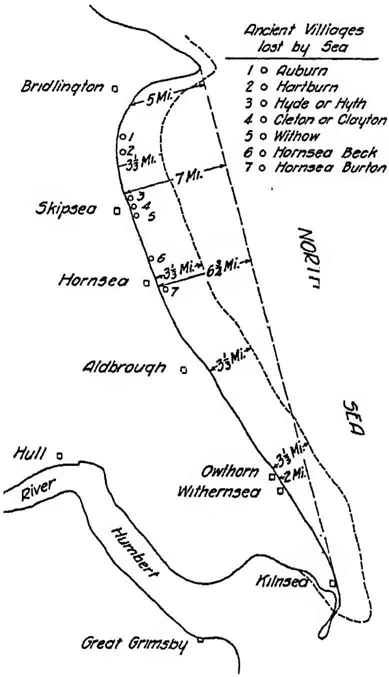


FIG. 211.—Changes in the Yorkshire Coast, England.

this portion of the continent was above sea level. The valleys of the St. Lawrence, the Hudson, the Delaware, and the former Chesapeake River have been traced far out to sea. The condition of the ancient valley of the Hudson, as shown in Fig. 210, page 346, illustrates similar conditions that prevail in many places. The changes in the land surface by erosion of the waves and by the deposition of material eroded from the exposed surfaces is and always has been of great importance.

Mr. E. R. Matthews states[10] that there is hardly a county of the east coast of England that has not had numerous towns and villages de-

10 Proc. Inst. of Civil Eng., Vol. 159, p. 77.

stroyed by the waves during the last few centuries, and he estimates this loss at approximately 1,800 acres per annum. Mr. Matthews estimates that the loss along the Yorkshire Coast has been at least nine feet per annum, and that the loss since the Roman invasion has been approximately as shown in Fig. 211.

In many cases material accretions are added to the lands by wave and current action, for example Dungeness Point on the south shore of England is said to have extended seaward over nine feet per annum between 1795 and 1850, thirteen feet per annum between 1850 and

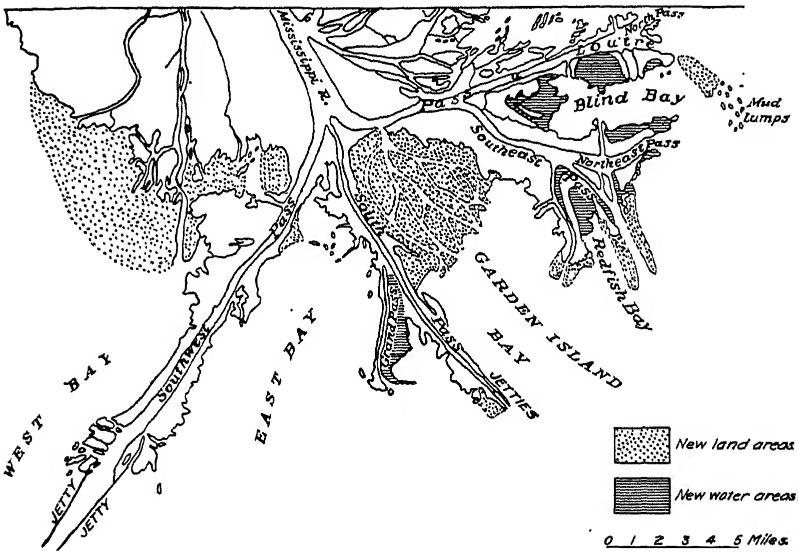


FIG. 212.—Lower End of the Delta of the Mississippi River.

1871, and eight feet per annum between 1871 and 1897, and that in consequence the light house had to be shifted three times during the past century.

The extended growth of deltas at the mouths of large rivers is illustrated by Fig. 212,[11] page which shows the lower end of the Delta of the Mississippi River. The Delta receives about 400,000,000 tons of sediment every year and is being built out into the sea at an estimated average rate of about 300 feet a year.

[11] Mud Lumps at the Mouths of the Mississippi, E. W. Shaw. Prof. Paper 85—B, U. S. Geological Survey.

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CHAPTER XIV

GEOLOGY

160. **Object of the Study of Geology.**—The primary object of the hydraulic engineer in the study of geology is to determine the structure of the earth insofar as such structures will influence his work in relation to:

1. The conditions favorable or adverse to the presence and permanency of surface or ground waters and their control or disposal.
2. The discovery, selection and utilization of adequate water supplies.
3. The storage and distribution of waters.
4. Securing and maintaining the qualities of water necessary for sanitary and economic purposes.
5. The reclamation and protection of communities, lands, structures and channels from the presence or encroachment of normal and abnormal waters.
6. The selection of sites desirable for safe and economical construction of dams, reservoirs and protection work.

The presence of surface waters and the flow of streams depend not only on the quantity and distribution of the rainfall but on the geological structure of the drainage area and the amount of water which on account of such structure will flow from the area without entering the ground, or which will be delivered to streams or lakes from the pervious deposits without sinking into the deep underlying strata entirely below the bed of the drainage system.

Navigation, water power, irrigation and water supply engineering depend primarily upon the availability of sufficient water either from surface streams or underground sources, both of which are largely dependent upon geological structure.

The occurrence of surface waters is obvious, but the possibilities of the presence of underground waters can be determined only by a knowledge of the local geological conditions. The presence of such waters and their character can often be inferred and often definitely determined, without expensive pioneer exploration by a knowledge of the geological conditions of the country.

The practicability of successful storage of waters depends upon the

nature of the foundation of the dam or embankments built to retain them and the character of the bed and banks of the ponds or reservoirs so created. The presence of cracked, fissured, faulted or cavernous rocks or of pervious deposits may make such structures impracticable either from the expense involved in the construction and maintenance of the work necessary to correct the unsatisfactory condition or on account of the excessive losses of water due to percolation. The feasibility of the distribution of waters through open channels for water supplies and navigation depends also upon the presence of favorable or unfavorable deposits and the condition of the materials through which such channels are to be constructed.

The mineral content of water depends on the mineral character and solubility of the geological deposits through which water flows from the catchment area to the point of utilization. Its sanitary character depends upon the conditions encountered in its flow which may be favorable either to the maintenance of organic purity or to its contamination by the wastes of civilization and manufacturing.

The protection or reclamation of lands from normal and occasionally abnormal conditions of flood and drought to which they may be subject is largely determined by the topography and structure of such land.

The foundations of structures and the suitability of sites for safe and economical construction and maintenance of dams, reservoirs, canals and their appurtenances are largely questions of topographical and geological conditions.

In all cases topographical conditions are more or less evident and can be determined in detail by surveys. Geological conditions can be determined only by expensive exploration and borings, which expense, however, can often be largely curtailed by a knowledge of local geology and of geological principles. Frequently even extensive exploration will not give the information needed without the interpretation which can be furnished only by geological knowledge.

161. **Rock Masses and their General Classification.**[1]—In general all materials forming part of the earth's crust, whether consolidated or unconsolidated, are termed rocks. These rock masses may be classified into four principal groups:

1. Archean Rocks, which while probably not parts of the original crust of the earth, constitute the earliest known rocks. The Archean rocks are believed to be the foundation over which later rocks were de-

[1] Physiographic Processes, J. W. Powell, p. 11.

posited and the source from which the sedimentary rocks have been most largely derived.

2. Volcanic Rocks, which result from flows of melted lava that have issued from the interior of the earth through volcanoes and volcanic fissures.

3. Sedimentary Rocks, which have been formed in the sea by the deposition of materials due to the denudating influence of atmospheric and hydrological agencies which continually act with destructive effect on preexisting rock beds and on the resulting decomposed material during its transportation. These materials have been deposited in more or less changed forms and have served to build up new strata which in their turn have been lifted up and exposed to like conditions and have served, together with the formations already exposed, to furnish the new material for still later deposits. These strata have been laid down in varying thicknesses but otherwise are somewhat like the leaves of a book with only the upturned edges accessible at the surface while their mass in general is largely overlaid by later deposits.

4. Mantle Rocks, which are the more or less superficial deposits of disintegrated indurated formations produced by the destructive action of the atmosphere, of water and of ice, and which either remain a decomposed mass over the parent rock or have been transported by various agencies to other localities where they remain a surface deposit of soil and subsoil, comparatively loose and unconsolidated.

162. **Historical Geology.**—The study of geology has occupied the attention of many able and eminent men for many years, and many sections of the earth have been studied in considerable detail. From the studies of conditions as they now exist, including the arrangement and characteristics of the strata, from the geological conditions now under process of development, and from numerous data too extensive to mention, conclusions have been drawn as to various conditions of the past, which, if summarized, will give the engineer a concrete idea of the manner of the growth of the continent, and will assist him in comprehending many local hydro-geological conditions which are less readily understood if examined as isolated and independent problems. The extent of certain geological deposits, the physical conditions that obtain therein, and the modifications of concomitant hydrographical conditions that result therefrom are in this manner more readily understood and appreciated. The geological deposits of greatest interest to the hydraulic engineer are those of sedimentary and glacial origin, for among these deposits are those which are of greatest importance as containing waters

available as supplies, and those deposits which from their absorptive qualities most greatly influence the flow of streams both from absorbing, retaining and supplying waters under favorable hydrological condition.

The hydrological character of the earlier rocks is not usually such as to render them available for water supplies, except through their cracks and fissures, which may be of local importance. The absence of absorptive qualities is, however, frequently of equal importance hydrologically on account of its important influence on runoff.

163. **Chronological Order of Geological Time—Division of Strata.**—From the earliest time the agencies now at work in the disintegration and rearrangement of geological deposits have been active in a similar manner but intensified at times by more extreme conditions of temperature and atmospheric activity. The entire time since scientific observations of geological conditions first began has occupied a comparatively few years, and the observed changes during that entire period have been limited but have served to indicate in no indefinite way the greater changes that have occurred in the past. Geological history as determined from the strata involves geological activities of millions of years and the changes which have succeeded each other have often been widespread and fundamental.

The chronological classification of the rock masses has therefore been based on the more radical changes which have resulted in: (1) the changed character of the strata themselves, and (2) the markedly different characteristics in the life existing at the time of formation.

During all these periods changes more or less complete were taking place in the relative elevations of the rock surfaces both by erosion and by disatrophic movements, to both of which are due the contour and limitations of the existence of the consequent later strata.

It is important to note that in many cases the deposits of different periods shade into each other through transition deposits more or less indeterminate, while in other cases the lines of demarcation are more obvious and the changes in character more complete.

The following list includes the most important divisions of geological time, arranged in chronological order, the earliest in time occupy the base of the column and the remainder occur as they would in their natural or normal positions.[2]

In no location is the above geological section complete but from the occurrence of these strata at various locations the sequence of formation has been determined.

[2] Chamberlain and Salisbury Geology, Vol. 2, p. 160.

Fig. 213 is a geological map of the United States, showing the general formations so far as they are known to occur at the surface. From these outcroppings the strata dip in general in the direction of the later deposits, sinking beneath the surface under the more recent formations, and can be reached at points below the surface of more recent strata only by deep excavations or by the drill. Excavations made on the outcrops of geological deposits will in general uncover only formations of a still earlier age.

Cenozoic	Present	Quarternary	
	Pleistocene		
	Pliocene		
	Miocene	Tertiary	
	Oligocene		
	Eocene		
Mesozoic	Upper Cretaceous		
	Lower Cretaceous		
	Jurassic		
	Triassic		
Paleozoic	Permian		
	Coal Measures—Pennsylvanian		Carboniferous
	Sub-carboniferous—Mississippian		
	Devonian		
	Silurian		
	Ordovician		
	Cambrian		
Proterozoic	Keweenawan		
	Animikean	Algonkian	
	Huronian		Pre Cambrian
Archeozoic	Archean		

164. **The Precambrian Rocks.**—At the beginning of the formation of the present sedimentary strata, the early Archean and Algonkian land areas were probably quite limited in extent, in comparison with the present exposed continental areas. The approximate boundaries, as far as known, and within the present area of North America, are shown in Fig. 214A.

The entire area, deep below the present surface, is supposed to be underlaid by Archean rocks of unknown thickness, or by some other base rock on which rests the later sedimentary deposits.

Ages before the formation of the present sedimentary deposits, the same processes had resulted in sedimentary deposits which, from the lapse of time and by the action of heat, pressure and other agencies, have been so changed and metamorphosed as to give many of them characteristics quite similar to the earlier Archean formations.

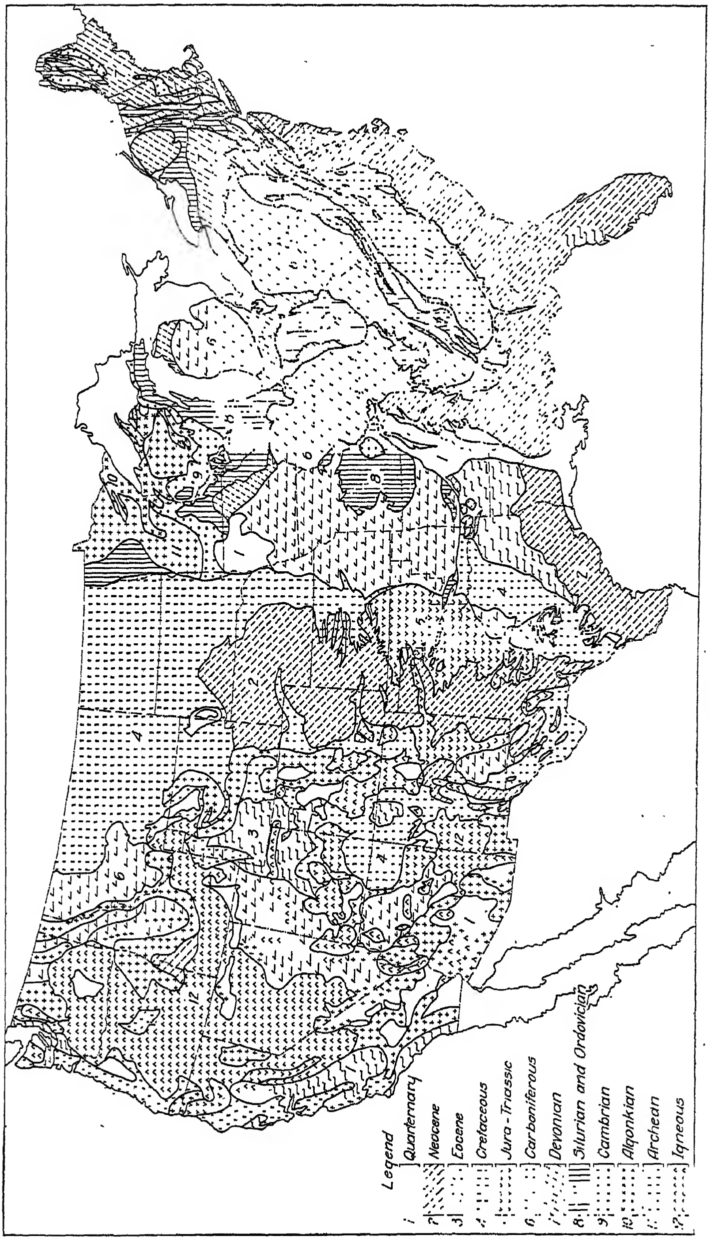


FIG. 213.—Geological Map of United States (see page 355).

The earliest Archean deposits are the Laurentian rocks, consisting of granites, syenites, and allied rocks. Of a later origin are the Algonkian deposits, which consist of crystalline magnesium limestone, quartzite, slates and schists of the Huronian period, which contain the iron ores of Minnesota, Wisconsin and Michigan. The later Algonkian rocks of the Keweenawan period, consist of sedimentary rocks, sandstones, conglomerates, and shales, with eruptive rocks containing the copper deposits of the Lake Superior region.

These rocks are flexed, folded, tilted and metamorphosed, showing evidences of upheaval and depression of the earth's crust of great magnitude and extent. With the exception of the eruptive rocks, most of the Algonkian rocks show evidence of sedimentary origin, indicating their derivation from a still more remote source, and that they are not themselves a portion of the original crust of the earth.

Subsequent to the formation of the Archean and Algonkian deposits, and during the periods of the formation of the earlier sedimentary rocks, the central part of North America, including the Great Lake region, was occupied by an interior sea, the depth and extent of which fluctuated repeatedly. The rise in sea level with respect to the neighboring lands at certain times, is believed to have been due largely to the fact that the lands exposed to the disintegrating and denuding forces of the atmosphere and of running water, were being reduced to lowlands, while the rock waste thus derived from them was being deposited in the sea, partly filling the basins. The water thus displaced rose, and even though the actual change of level was slight, it was sufficient to cause the sea to extend far over the lands on account of their greatly reduced elevations. These changes in the relation of land and sea were also doubtlessly caused by warpings and dislocations of the earth's crust. It is clear that many such warpings have occurred, for strata which must at the time of their deposition have been essentially horizontal and continuous on the sea floor are now found widely scattered over the lands, and in a great variety of warped and folded forms. The reasons for these deformations can not be told with certainty. Gravity or the tendency of the earth's mass to settle towards its center, has probably caused the sinking of certain excessively loaded sections of the ocean floor which might have been less firmly supported from beneath than in other localities. It is also possible that the cooling of the earth has caused contraction, which has resulted in the outer portions accommodating themselves to the shrinking nucleus by warping or wrinkling.

Some of the changes that probably took place in the extent of land in

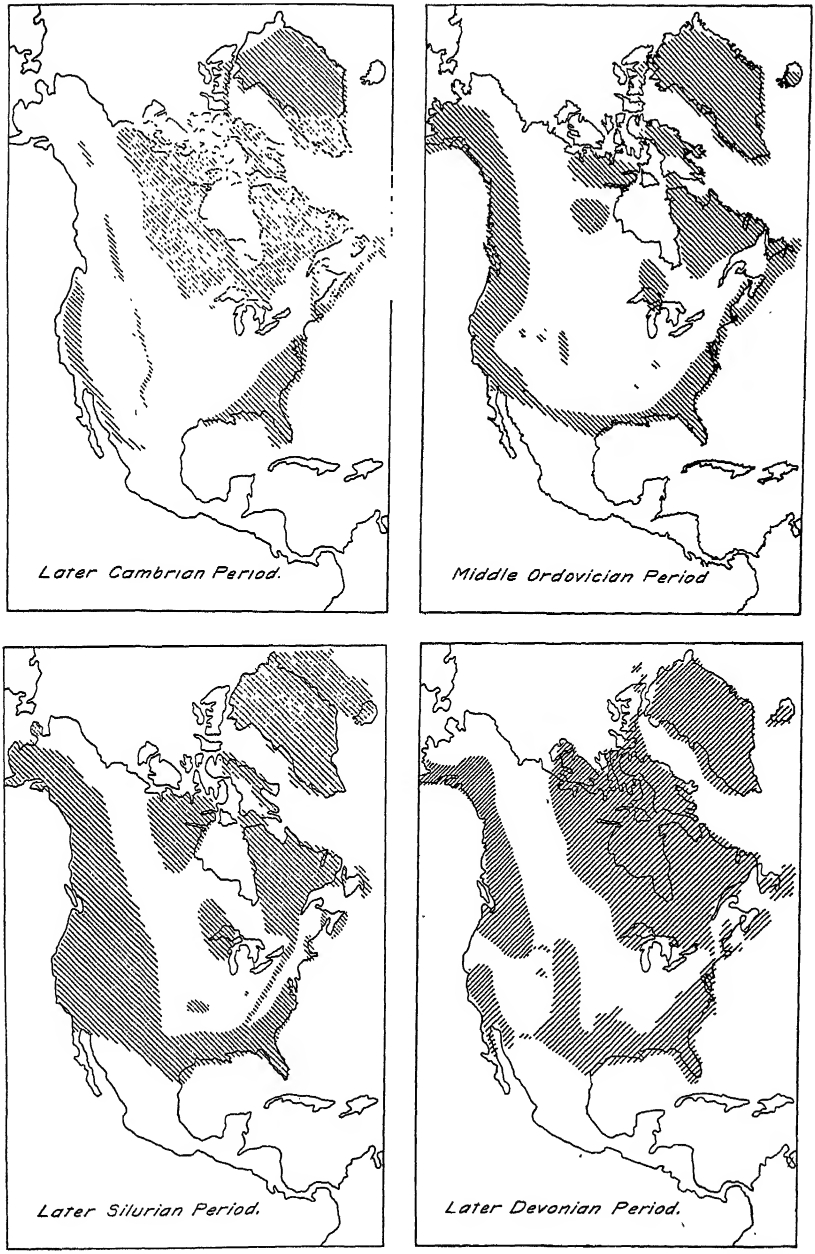


FIG. 214.—Hypothetical Maps of Possible Relations of Land and Sea in North America at Various Geological Periods (see page 358).

North America during the formation of the sedimentary strata are indicated by the hypothetical maps of Fig. 214.[3]

165. **The Upper Mississippi Valley.**—To give a clearer idea of geological growth, and of the geological structure of the earth, a more detailed study of some particular locality is desirable. This will enable the general features of geological structure to be more clearly understood than would be possible with the discussion of the larger area of the continent, or of the entire United States, where, from the multitude of details, the general principles are likely to be obscured.

For this purpose, the Valley of the Upper Mississippi River has been selected, and in the study of the geological history of this territory it should be understood that it is but an example of quite similar conditions which have occurred in all portions of this country and of other lands. All lands have had a corresponding geological history, more or less varied, but in a general way controlled by similar laws, which have resulted in similar general conditions, more or less modified in detail as the controlling factors have differed in their nature and extent.

The Upper Mississippi Valley, together with much adjoining territory, consisting of the Lake Michigan and Lake Superior basins and the valley of the Red River of the North, had a common geological origin and history, and, at a comparatively recent geological period, a common drainage system, all their waters emptying through various channels into the Mississippi River and thence into the Gulf of Mexico, until subsequent geological changes so modified the topography as to produce the present drainage systems.

The territory here considered comprises the greater portion of Illinois, Iowa, Wisconsin and Minnesota, and a small portion of North-eastern Missouri and North-western Indiana, and embraces within its area much of the richest farming country of the United States, a country largely settled, and having numerous thriving and growing communities. In the north are forests of pine, and rich mines of iron and copper, while in the south are valuable deposits of bituminous coal and fire clay. Deposits of valuable building stone are found throughout its extent. It contains all the resources necessary for a rich and populous manufacturing and agricultural development.

In order to show the details of geologic growths and their effects on the present geological and hydrographical conditions, a series of hypo-

[3] See Bul. No. 11, Illinois Geological Survey; also Cleland's Geology, and Willis-Salisbury Outlines of Geological History.

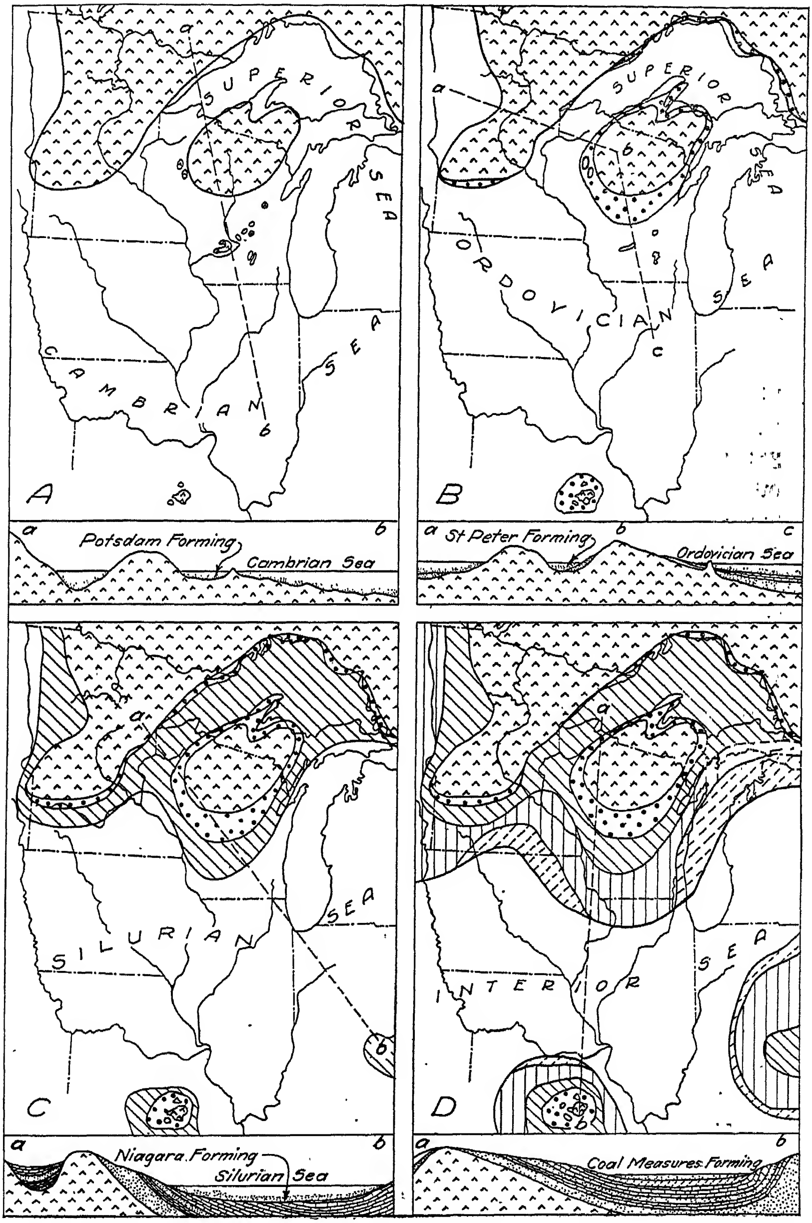


FIG. 215.—Hypothetical Maps and Sections of Possible Relations of Land and Sea in Upper Mississippi Valley during the Formation of Various Geological Deposits (see page 360).

thetical maps has been prepared (see Fig. 215) showing the upper Mississippi Valley at various periods in its geological history.[4]

166. **The Cambrian Period.**— At the beginning of the Cambrian Period some diastrophic movements produced extended depressions of the earth's crust and caused the sea gradually to extend over the low interior of North America, expanding on all sides, until by the end of the period, all the central portion of the continent and most of the western and northern portions were submerged. An extensive highland belt (The Appalachian Uplift) separated this interior sea from the Atlantic on the east and long discontinuous mountain belts in the far west and northwest, separated it from the Pacific. On the north a great V-shaped land area in Canada (The Laurentian Outcrop), formed at that time the main part of the land of the North American continent. Two highlands, outliers of the Laurentian land, apparently escaped submergence: one in the Adirondack region of northern New York, and the other in the highlands of northern Wisconsin. Around their subsiding borders were spread out in late Cambrian times extensive deposits of sand. From the Wisconsin highland region, the sand reached southward on the sea floor well into Illinois, and now constitutes the Potsdam sandstone formation.[5]

During this age the principal part of the upper Mississippi Valley (Fig. 215A) was under the sea, which throughout Wisconsin was comparatively shallow and contained many quartzite islands of the Huronian formation, which yet rear their heads above the Potsdam outcrop. This Potsdam deposit consists mostly of sandstone derived from the broken quartz grains of the decomposed granites and allied rocks. These deposits, close to the Archean land, consist of coarse quartzose sand rock, very open, porous, and free from the iron, lime and clay, which, in the higher strata, are found associated with it. The Cambrian Sea held in its depths some of the earliest forms of animal life. Myriads of small shellfish, the remains of which may be seen in many of the Potsdam outcrops, inhabited its waters.

Although commonly spoken of as a single geological stratum, the Potsdam is by no means homogeneous in texture throughout. During its formation a vast period of time elapsed, very many disturbances occurred, and the circumstances of deposition of the different portions of the stratum varied greatly. Those variations were almost or quite as great as those that marked the changes to subsequent geological ages.

The evidence of this, in portions of Wisconsin, is so marked that

[4] See The Hydro-Geology of the Upper Mississippi Valley, by Daniel W. Mead.

[5] Bulletin 11, Illinois Geological Survey.

Professor T. C. Chamberlain has classed the Potsdam strata of Central and Eastern Wisconsin in the following subdivisions:

Sub-Divisions of Potsdam Deposit.

	Thickness Feet.
Sandstone (Madison)	35
Limestone shale and sandstone (Mendota)	60
Sandstone, calcareous	155
Bluish shale, calcareous	80
Sandstone, slightly calcareous	160
Very coarse sandstone, non-calcareous	280
Total	770

The thicknesses given are subject to wide variation. As a rule they thin out quite rapidly in Wisconsin, northward from Madison, and increase in thickness to the southward into Illinois.

Professor W. H. Winchell notes a somewhat similar classification in Minnesota. In a deep well drilled in East Minneapolis he found the following series of Potsdam rocks.[6]

Section of Artesian Well, East Minneapolis.

		Thickness Feet.
Sand (Drift)		42
Blue limestone, Trenton		28
White sandstone, St. Peter's		164
Red limestone, Lower Magnesian		102
Gray limestone, Lower Magnesian		16
Potsdam:		
White limestone, Jordan	116	
Blue shale, St. Lawrence limestone	128	
White sandstone, Desbach	82	
Blue shale	170	
Sandy limestone	9	
White sandstone	130	
Sandy marl, Hinkley	8	
White sandstone	79	
Red marl	57	
Red sandstone	290	
		1,069
Total		1,421

Although the classification into these sub-divisions is warranted by well-defined beds around Madison, Wisconsin, in eastern Wisconsin and in Minnesota, yet, owing to the thinning out or disappearance of these strata or by the multiplication of sub-divisions, the local variations are so great that in many places it is impossible to classify the strata found, under any general classification except the general name, Potsdam; for the limits of this formation, as a whole, are well and clearly defined.

6 See Geology of Minnesota, Vol. II, p. 279.

As indicated in the foregoing tables, the Potsdam varies greatly in its character throughout its extent, not only from shale and limestone to sandstone, but also in the character of the sandstone, which is mostly

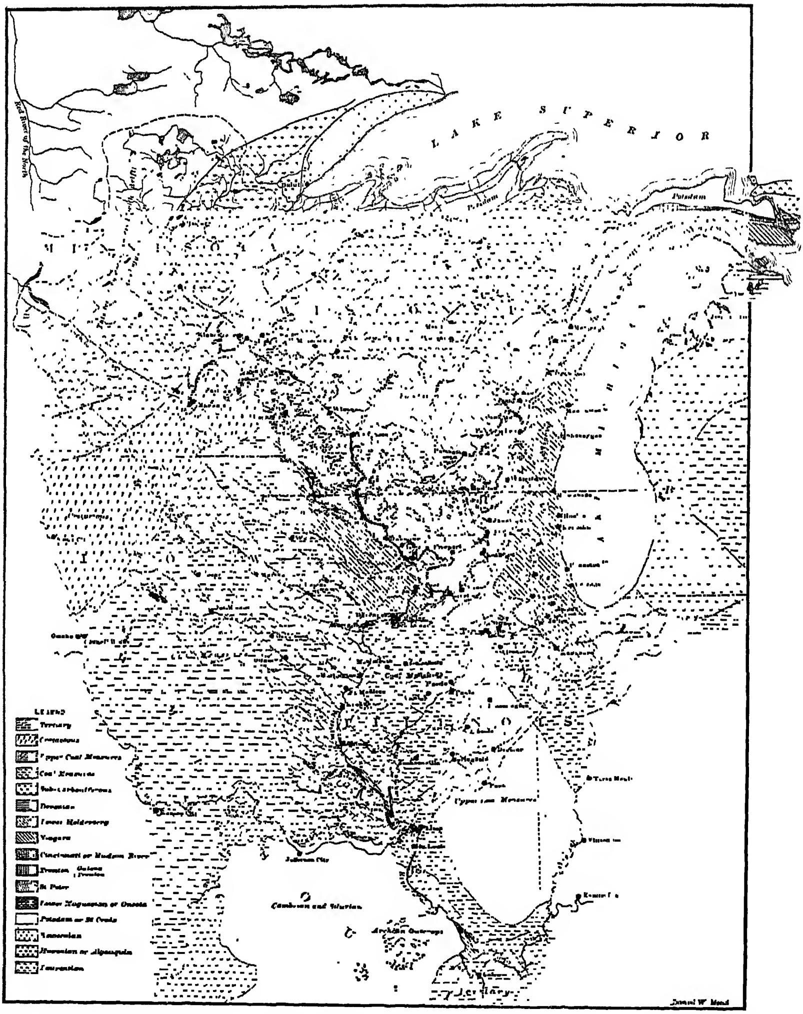


FIG. 216.—Outcrops of Various Indurated Formations in the Upper Mississippi Valley, Drift Mantle Removed (see page 365).

fine-grained, but becomes coarse-grained in its lower strata, and passes into a conglomerate near its margin, the shore of the ancient Archean land. As may be understood from its physical character, it readily transmits the water which it receives at its outcrop, either from rains or

from the numerous streams which flow over its exposed surface, the extent of which may be judged from the maps. The outcrops of the Potsdam occupy about 14,000 square miles in central Wisconsin, extending in a crescent-shaped tract around the Archean outcrop. (Fig. 216, page 364.) Below the later sedimentary deposits it occupies most of the area of the Upper Mississippi Valley and furnishes the source of thousands of private and public water supplies.

167. **The Ordovician Period.**—During the Ordovician period the interior sea continued to expand beyond its limits in the Cambrian period through local and temporary oscillations of its floor, and its shores kept changing their outline. In northern Illinois, a change from sandy sediments to sandy limestones, and finally to pure, fine-grained limestone occurred as the period progressed, and indicates that the surrounding land areas suffered great reduction under the destructive actions, erosion and transportation, so that during the middle and late Ordovician period, the waters of the interior sea were no longer clouded by riverborne sediment, and the deposits made were limited almost wholly to shells, corals, and other organic remains. The early Ordovician sediments are the Lower Magnesian limestone and the St. Peter sandstone. Above them is the Trenton limestone, containing an abundance of fossils which indicate that the water was relatively clear, shallow, and rather warm. (Fig. 214 B, page 359.)

In the Upper Mississippi Valley two of these deposits are of considerable hydrological importance: the Lower Magnesian or Oneota Limestone and the St. Peter Sandstone.

The Lower Magnesian is a dolomitic limestone, coarse, irregular in stratification, often inter-stratified with shale or sandstone layers and limestone breccia, which last, occurring in clusters or heaps, often gives the upper surface a billowy appearance and causes it to vary greatly in thickness. The variation in thickness seems to be more marked in Wisconsin than elsewhere.

Although undoubtedly cracked and fissured to some extent, it seems to be in general free from these disturbances and to offer a quite uniform and homogeneous mass to prevent the upward passage of the waters contained in the Potsdam stratum below it. This stratum is found from 65 to 260 feet thick through Wisconsin and is from 105 feet to 170 feet thick in northern Illinois. It seems to thicken quite rapidly to the southward, and is found to be 490 feet thick at Joliet, 500 feet thick at Streator, and 811 feet thick at Rock Island. A flow of water, which may be derived from the underlying Potsdam sandstone, is sometimes found in the softer portions of this stratum.

Over the Lower Magnesian limestone in the Upper Mississippi Valley lies a remarkably uniform quartzose sandstone. It is uniform in material and thickness, and quite covers all the irregularities in the surface of the underlying limestone, except at some points in Wisconsin where it is entirely pinched out and the Trenton limestone lies directly on the Lower Magnesian limestone. The average thickness of the St. Peter sandstone throughout the territory under discussion is probably about 150 feet, although in Wisconsin Chamberlain estimates its average thickness as only about 80 feet. This deposit is believed to have been formed in a shallow sea by the decomposition of the Archean and Potsdam rocks. The hypothetical condition of the Upper Mississippi Valley during the formation of the deposit is shown in Fig. 215B, page 361. No fossils have been found in this rock, and its formation marked an epoch probably unfavorable to the existence of life.

This stratum has an outcrop of about 2,000 square miles in Wisconsin, and also crops out at several points in Illinois along a line of upheaval which passes southwesterly from Stephenson County to the vicinity of La Salle, bringing the St. Peter to the surface along the Rock River at Oregon and Grand Detour, and along the Illinois River from La Salle to Ottawa. The Lower Magnesian limestone is also brought to the surface at Utica by this uplift. The St. Peter sandstone is an important water-bearing stratum, although its outcrop is so low that the pressure of its water is usually much less than the water of the Potsdam.

Although apparently no life existed in this region during the formation of the St. Peter sandstone, yet conditions favorable to the existence of life again returned, accompanied by geographic changes in the relation between the sea and the land, and extensive beds of limestone were again deposited. These constituted the limestones of the Trenton group, which may be divided into various substrata more or less distinct in character. Of these the Galena limestone is, perhaps, the best known, but for the purpose of this discussion the Trenton may be considered as a whole, inasmuch as its general character is approximately uniform. This deposit through its cracks, fissures and channels furnishes water in limited quantities for domestic use.

Toward the close of the Ordovician period, the Trenton limestone deposit was buried by a great sheet of mud over 100 feet in thickness, which has since been consolidated into the Hudson River or Cincinnati shale. By the time this formation was deposited the interior sea had begun to shrink, and the surrounding land to emerge, exposing broad coastal plains, from which and across which, the sediment was washed into the sea.

Geographic changes of great extent now occurred. Intense deformations in eastern New York added to the width of the Appalachian mountain belt, while in the Mississippi valley region there was a very extensive emergence of land, with, however, little or no deformation of the rocks. The interior sea shrank to smaller proportions and marine life became seriously restricted. These parallel changes of the geography and the fauna are the reasons for separating the Ordovician from the succeeding Silurian period.

168. **The Silurian Period.**—With the changes that occurred at the end of the Ordovician Period most of the interior of the continent became dry land, but as the Silurian period advanced, the inter-continential sea once more encroached upon a part of the interior of the continent. It expanded over Illinois and Michigan and southwest toward Arkansas and Missouri, where it was presumably bordered by a land area. (See Fig. 214C.) In this interior sea a great limestone formation outcrops continuously for more than 1,000 miles from central New York to northeastern Iowa and is widely exposed about the Great Lakes. It takes its name from the Falls of Niagara, for which the hard limestone is chiefly responsible. Like most limestone the Niagara Limestone was originally an organic deposit, made up of an accumulation of calcareous skeletons and shells of marine animals, worked over by the waves and currents, and ground to a fine calcareous mud. One of its distinctive features is its wealth in fossils remains. Evidently, the interior sea was nearly free from river-borne sediment in most places; hence, it is believed that the surrounding lands were low and the rivers sluggish. (Fig. 215 C, page 361.)

169. **The Devonian Period.**—At the close of the Silurian period, the emergence of large portions of the interior of the continent greatly restricted the inland sea. Subsidance of the land and expansions of the sea were renewed in the Devonian period. (Fig. 214 D, page 359.) By the middle of this period, the most of the upper Mississippi and the Ohio River were again below the sea. The Devonian occurs as surface rock in northwestern Indiana, where it is almost concealed by glacial drift. There is a Devonian outcrop near Milwaukee, Wisconsin, and near Rock Island, Illinois.

During the greater part of the Devonian time most of Wisconsin and northern Illinois was above sea level, and may have been a part of a large land surface stretching south toward the Ozark uplift, of Missouri. Near the close of the Devonian period, when the sea again occupied much of this region, sands were sifted down into the open joints of the

lower strata, and with it the fossil remains that marked the Devonian period in those states.

170. **Carboniferous Period.**—The strata of the coal measures are the youngest bedrock of the upper Mississippi valley, and are therefore the highest rock formation wherever they exist in this region. The Pennsylvania system lies at the north margin of the great Illinois coal measures, and in most cases is found in isolated patches which lie north of the margin of the continuous coal area measures, and are the remnants of a continuous series which once extended farther to the north.

The coal measures consist primarily of shales and secondarily, of sandstones. Among the shales beds of coal and black seams of carboniferous matter are common. The unexposed or fresher exposed shales are usually blue or drab. They occur in thick massive beds but soon weather into thin friable laminae and become lighter in color.

Sandstone often consists of thick massive beds, but sometimes occurs as thin layers interbedded with the shales. The base upon which the coal measure rests is very regular in some places; at the south, it consists of Devonian limestone, while in the north, coal measures rest on the Niagara limestone.

The probable extent of land and sea during this age is illustrated by Fig. 215 D, page 361, which shows the further recession of the sea and the consequent limitation of the strata then under process of formation.

This age ushered in an epoch of life very different from any which had preceded it. Its deposits were comparatively local in character, and although they have in a general way been correlated, yet there is a greater variation in these strata than in those of any preceding deposits. Especially is this true in those of the coal measures proper. These deposits seem to have been made in shallow seas, lakes or swamps of limited extent, rather than in a broad and deep sea such as those in which most of the preceding deposits had been formed. Hence, great local variations are observable and the strata have commonly a much more limited geographic extent. This age witnessed the formation of extensive beds of limestone, sandstone, shales and coal.

171. **Sedimentary Deposits of Later Periods.**—The periods briefly outlined above, in order to furnish some conception of geologic growth, were succeeded in other parts of the country by numerous other more recent sedimentary deposits outlined in Sec. 163. These may be of great importance in the study of the hydrological phenomena of the locality in which they occur. Their consideration in detail is not considered of importance in this chapter as the entire subject of geology

must be taken up in much greater detail than is possible in one volume in order to give sufficient knowledge for its intelligent application to the work of the engineer.

172. **General Characteristics of the Strata.**—It should be understood that lines of exact demarkation seldom exist between the various strata. One stratum usually passes gradually into another. Changes in the controlling influence which modify the deposition were usually not radical and they obtained only gradually. Thus, in passing from sandstone to limestone, the upper strata of the sandstone will usually be found somewhat calcareous, and the lower strata of the limestone somewhat silicious.

A like condition applies to the character of the stratum throughout its geographic extent. The conditions at one point may have been such as to favor the formation of limestone deposits, while those at a point more or less remote may, during the same period, have been favorable to the formation of shale. We thus find widely different strata belonging to the same age. Hence, a stratum may within a short distance merge from a sandstone into a limestone, from a limestone into a shale, or the reverse, or from a coarse-grained stone to a fine and more impervious one. Or a stratum may even have been entirely lost by reason of a local elevation which raised the rock at that point above the sea level, thus preventing deposits, or by the existence of local ocean currents which might accomplish the same result. The more widespread the conditions controlling deposition, the more uniform is the character of the resulting stratum throughout its extent. The character of the rock deposit which we may encounter in drilling is often highly problematic, and it is only by an extended examination of facts as they have been found to exist, and by their proper correlation, that we may arrive at conclusions as to what we must expect in new and untried localities. The farther the point in question lies from those where the character of the sub-strata is known, the greater is the uncertainty respecting it.

173. **Modifications of the Strata.**—The original extent of the various sedimentary strata of the Upper Mississippi Valley was much greater than the present geological map of the region would indicate. Hundreds of feet in thickness have been disintegrated and eroded by drainage waters. The Hudson River shale, while now encircling Central Wisconsin and Central Northern Illinois as a narrow belt (Fig. 216, page 364), undoubtedly once covered a much greater area, as did the strata of the Niagara group. The section through Elk Mound shows

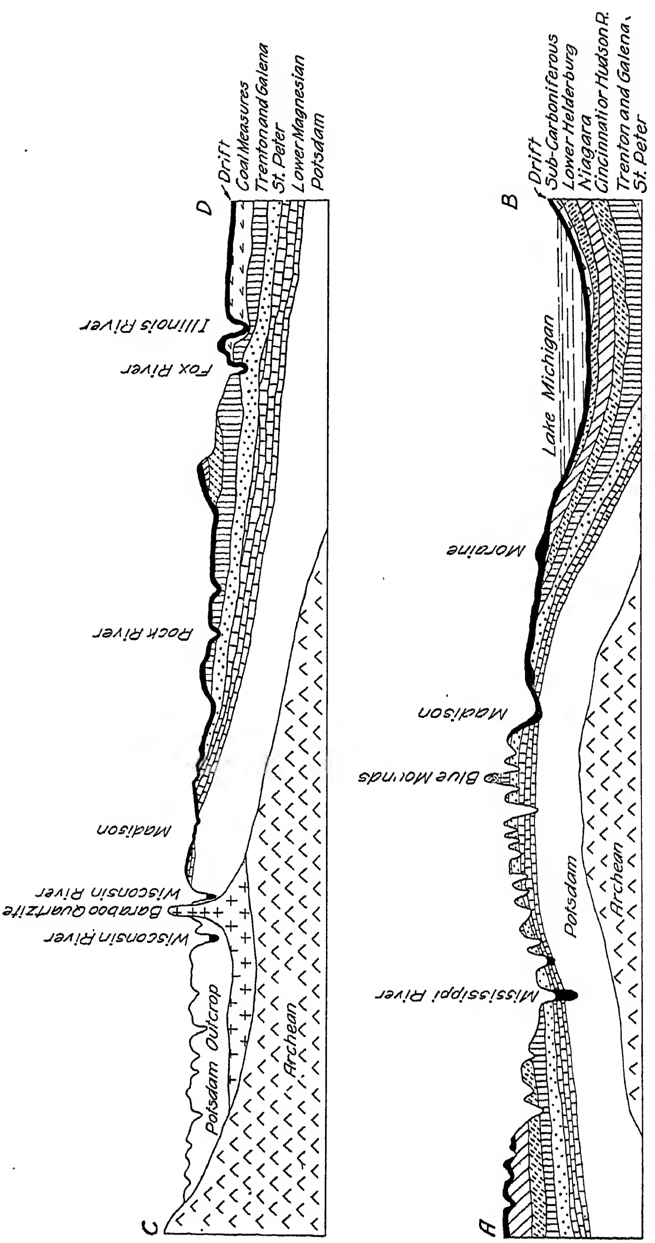


FIG. 217.—Geological Sections in the Upper Mississippi Valley (see map p. 364).

the present geological condition, while the prolongation of the limiting bed and surface planes of the strata indicate their probable original extent. (A–B, Fig. 217.)

It must also be understood that the sedimentary strata, although originally deposited as more or less uniform sheets, each overlying the strata below, do not exist in this uniform condition at present; for many disturbances, caused by upheavals and depressions in the crust, (Fig. 218), have opened cracks and fissures and have caused relative

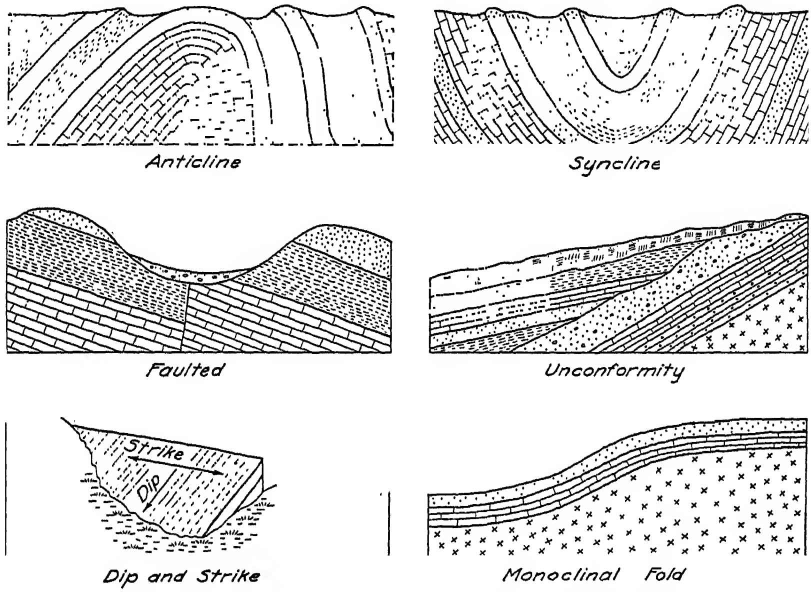
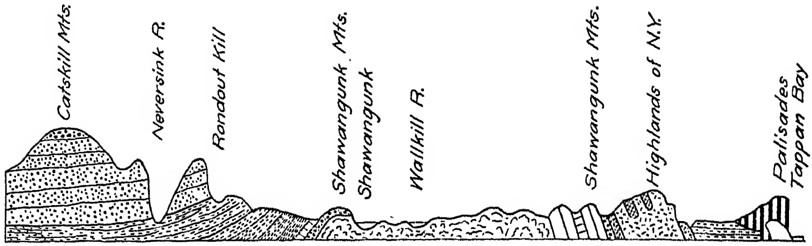


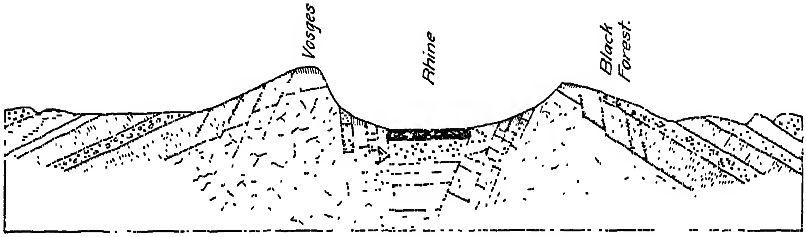
Fig. 218.—Some Structural Deformations of Indurated Rocks.

displacements of the strata (Fig. 219, page 372), amounting in some cases to hundreds of feet. The extent of the cracks and fissures caused by these disturbances of the strata may be judged by a visit to any quarry. Cracks and fissures largely modify the hydrological conditions of the various strata, frequently permitting the passage of the waters from one stratum to those below or above, and in the latter case giving rise to springs.

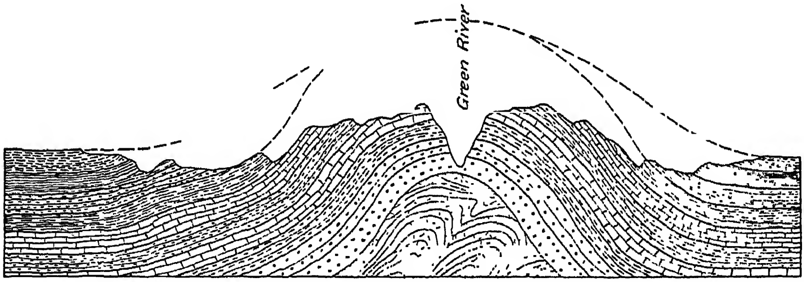
In the driftless area of Wisconsin are many sink holes and caves produced by the solvent action of underground drainage passing through joints and fissures in the Galena, Niagara and Lower Magnesian Limestone. The sink holes are the entrance to underground drainage channels. Some are dry and others contain water, showing the clos-



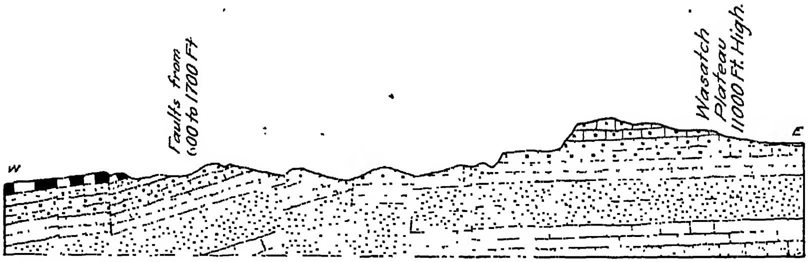
Section from the Catskill Mountains to the Hudson River (Mather)



Section across the Vosges and Black Forest (Penck)



Generalized Section thru the Uinta Mountains from North to South (Powell)



Section East and West in Central Utah Showing Numerous Faults (Dutton)

FIG. 219.—Some Structural Deformations Producing Topographical Relief (see page 371).

ure or incomplete development of the underground drainage. The caves are frequently several hundred feet in length and vary greatly in height and width. These caves are limited to the driftless area with the exception of a few minor developments near the border of the drift. Apparently the glaciers eroded most of the superficial rocks in which caves were developed in preglacial times.

The surface of the underlying Archean rocks slope downward in all directions from their outcrop in the extreme northern portion of this valley, being about 2,000 feet above sea level at their highest outcrop, and perhaps fully as much below sea level at their lowest point. The super-incumbent sedimentary strata follows this general slope. The Potsdam strata, however, thicken rapidly to the southward, as does the Lower Magnesian limestone, so that the higher strata have not as great a rate of inclination as the dip of the Archean rocks indicate. (Fig. 217, C–D.)

The north and south section illustrates this fact, and shows, moreover, that the surface follows the general dip of the strata at present, as it has done through all past geological ages; the outcrops of the older geological deposits being found at the higher elevations. In traveling from the original Archean nucleus in any direction the traveler will descend in elevation while he ascends in geological succession, passing over each of the deposits already described as he approaches the sea level.

During the ages here briefly reviewed, this territory had gradually arisen from the ocean. The carboniferous deposits mark the last age of submergence in this area, with the exception of certain minor Cretaceous areas in Northwestern Iowa.

174. **Pre-Glacial Drainage.**— With the earliest appearance of the land above the sea, the formation of a drainage system began. The atmospheric agencies disintegrated the softer portions of the strata and carved the rocks into various forms as their varying hardness permitted. The drainage waters carried the residuary matter to the sea, thus excavating deep drainage valleys, and forming the later strata by the deposition of the material.

The subsequent alteration of these drainage valleys has rendered it almost impossible to conceive of their early character and extent. The hill-tops were higher and bolder than at present. The valleys, deeper, more narrow and more rugged, occupied in many cases locations quite different from these now occupied. The Lake Michigan valley was then occupied by a river which flowed from the north through the present southern extremity of the lake, at an elevation some hundred feet

below the present lake level. This river, with a southwesterly course and passing probably not far from the present site of Bloomington, Ill., emptied its waters into the Mississippi near the present mouth of the

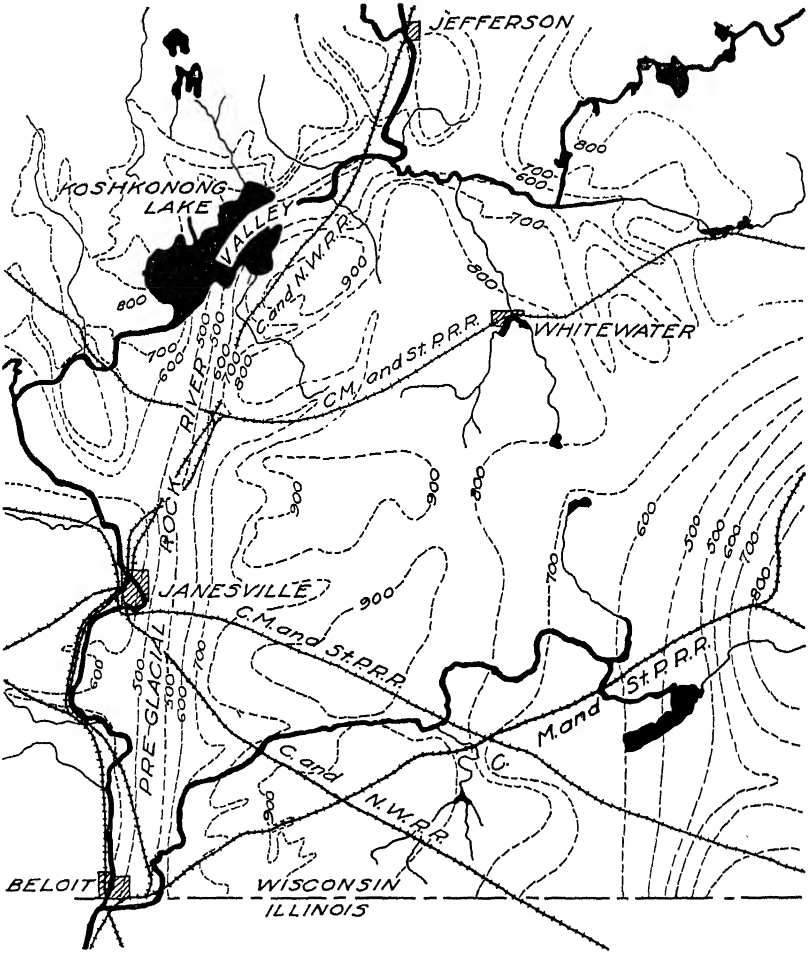


FIG. 220.—Present and Preglacial Valleys of the Rock River in Southern Wissin.*

Illinois River. A light soil covered the valleys and the depressions of the hills, furnishing a scant vegetation for the sustenance of animal life. The mammoth and the mastodon, whose descendant, the modern elephant, is no longer native of this continent, roamed through these early valleys, probably a co-inhabitant with primitive man.

*W. C. Alden, Professional Paper No. 34, U. S. Geological Survey.

The Mississippi River occupied to a considerable extent its present course. To this, however, there are local exceptions, notably at St. Paul, La Crosse, Rock Island and Keokuk, where the rock-bottomed rapids testify to a diversion from the ancient bed. The river then probably drained a much larger territory than at present. It also flowed at a level from 100 to 250 feet lower than its present one. It is difficult to picture the Upper Mississippi Valley as it then existed, but those who are familiar with the driftless area of Wisconsin, north and west of the Wisconsin River, including the Dells and country about Devil's Lake, can form some conception of the early topography of this whole area. This region of Wisconsin has been less altered than any other in the district considered; yet its valleys, which were then much deeper than now, have been deeply filled by the fluvial and lacustrine deposits of the drift period. (Fig. 220, page 374.)

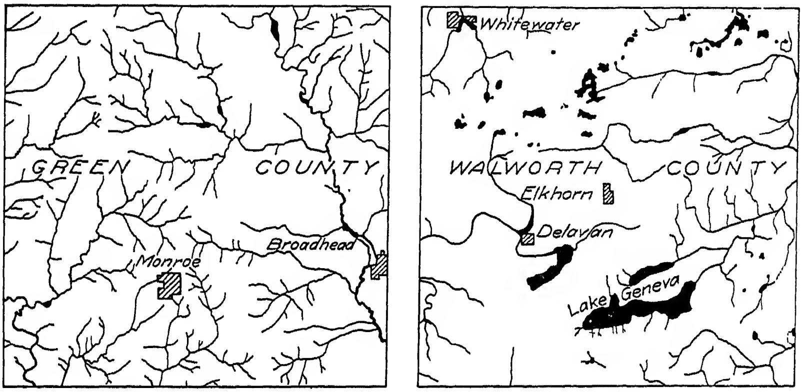


FIG. 221.—Comparison of Drainage Systems of Unglaciated (Green County) and Glaciated (Walworth County) Areas in Wisconsin.

The principal existing streams of this area, and to some extent their lateral valleys, have been greatly modified by the subsequent events of the Glacial period. A comparison of the present drainage system of Green County, Wisconsin, located within the driftless area, with that of Walworth County, Wisconsin, within the glaciated regions shown in Fig. 221.

175. **The Glacial Period.**—From causes not thoroughly understood, the consideration of which is unnecessary for the purpose of this chapter, there followed periods of great cold; of long winters and short summers and perhaps of greater average precipitation than at present, which fell as snow over the northern regions and which the heat of the short summer was wholly inadequate to melt. The result was the ac-

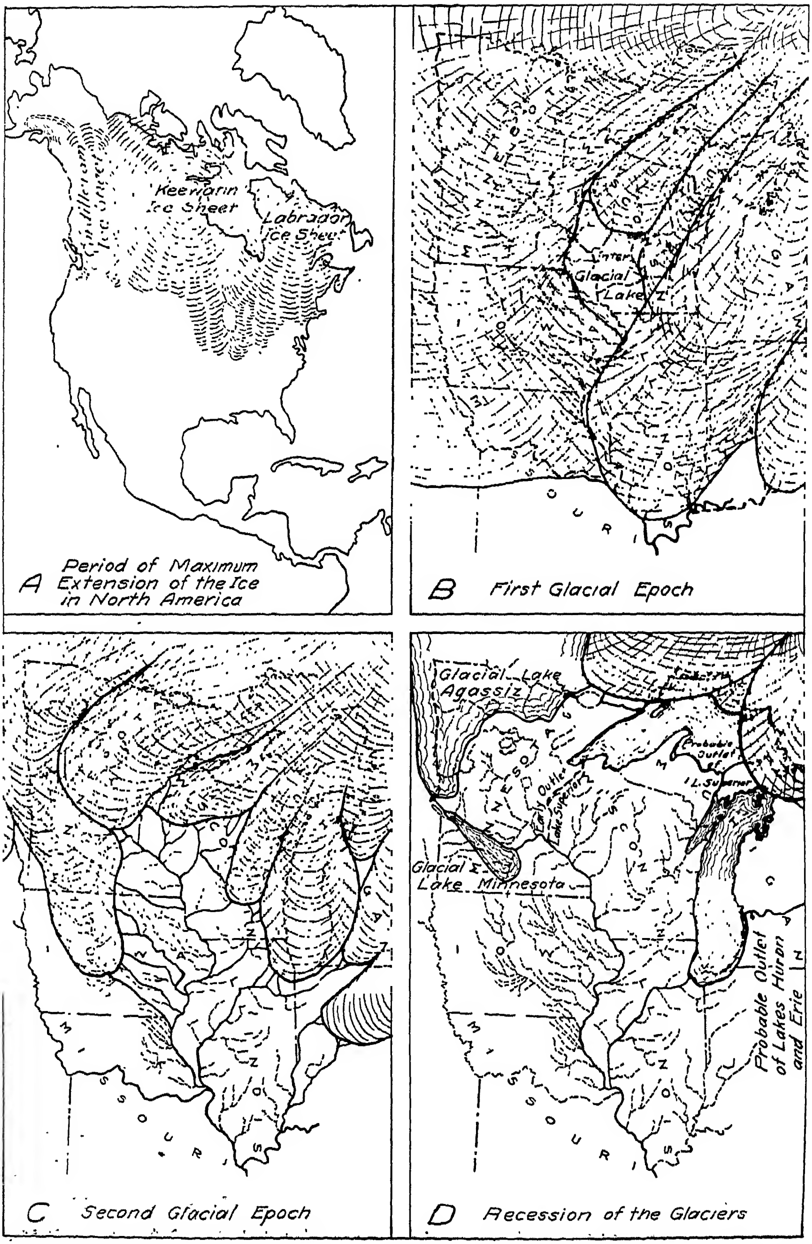


FIG. 222.—Hypothetical Maps of Conditions in North America and in the Upper Mississippi Valley during the Glacial Periods (see page 377).

cumulation of vast snow fields, thousands of feet in thickness, similar to those which now exist in Greenland and Alaska and in the higher altitudes of the Alps, the Himalayas and the Rocky Mountains. The weight of the superincumbent mass, greatest in depth in the north where the summer heat never penetrated, not only compressed its lower layers into ice, but forced them to flow in great glaciers to the southward. (Fig. 222, A.) Their extent in this direction was limited only by the conditions of equilibrium between the melting of the ice mass and its motion. The effects of the flow of these vast ice rivers over the irregular and deeply marked drainage depressions can be easily understood. The rocky hillsides were worn and broken into dust and fragments; huge boulders were torn off and transported hundreds of miles; and the valleys were filled up with the accumulating debris, which was more or less sorted and arranged by the sub-glacial waters. At least two epochs of glaciation, more or less distinct, can be traced in the Upper Mississippi Valley. (B and C, Fig. 222.) These have been perhaps the most marked causes in the creation of the present conditions, at least in so far as they are related to civilized life. To this period the agricultural lands of Minnesota, Iowa and Illinois owe their character and fertility, and their ability to maintain the population now within their borders. The drainage system was altered and the topography was greatly changed and re-wrought. Not only were the valleys filled up and the hills cut down, but a new class of topographical features was introduced.

176. **Work of Glaciers.**—While flowing water can transport only debris of a coarseness depending upon the velocity, moving ice will transport the largest rock as well as the finest material. The ice deposits its heavier material upon melting, most of the finer particles being often lost in the floods which result from the melting of the ice. The material pushed up or deposited in this manner by the ice is termed a "moraine," and when it marks the termination of the ice-flow, a "terminal" moraine. Such is the Kettle Moraine, which extends across the entire territory here considered. When formed on the side of the moving ice capes it is termed a "lateral" moraine, and two of these may be joined into a "medial" moraine.

Upon the melting of detached ice masses surrounded by extensive morainic deposits about their edges, kettle holes were formed which resulted in lakes and swamps. (See Fig. 200, page 339.)

The streams of water resulting from the rains and melting ice, frequently cut open channels in the glaciers and sweep into them vast quantities of material which is there worked over and sorted by the flood, and

deposited as a delta at the end of the glacier, or in long lines between the streams of ice, where it is left on the melting of the ice as ridge-like deposits called kames.

Fig. 222 B is a hypothetical map of the conditions of the Upper Mississippi Valley during what is usually termed the first glacial epoch, or at the time when the ice had reached its greatest southern extension; while Fig. 222 A shows the same conditions for the continent. The limits of the ice are still marked by ranges of hills of morainic material, the nature and character of which offer conclusive evidence of its origin. Many of the topographical features of the first glacial epoch have been greatly modified by subsequent glacial events and by atmospheric and aqueous erosion during the time which has since elapsed. The kettle holes and lakes have been gradually filled and they are now mostly swamps or peat-bogs, and deep lines of drainage have been cut through the glaciated area. This process has been greatly aided by the drainage waters of the second glacial epoch. During that epoch the extent of the ice capes was much more limited than in the first (Fig. 222 C), and as its period was more recent, its topographical features are more marked. Within the kettle moraine, which marks its limits, are found the numerous small lakes which form so striking a feature of Wisconsin and Minnesota scenery.

177. **Glacial Recession.**—With the recession of the ice capes the development of a new drainage topography began. The floods which came from the melting ice, inundating great tracts of country especially along the Mississippi River, gave rise to lacustrine deposits of considerable depth, known as "loess," a deposit consisting mostly of sand with some little clay, and so pervious as to offer little hinderance to the flow of drainage waters. The glacial waters had begun to excavate channels for their flow in their earlier deposits, and this process was continued in the lacustrine districts as the lacustrine conditions ceased to prevail. The old Michigan valley had been filled at the southern extremity of the present lake, and the waters being dammed in by the receding glacier from the present outlet of the lake, found a passage through the present valley of the Illinois River. The waters of Lake Agassiz, (Fig. 206, page 343) which was the progenitor of the present Lake Winnipeg, with an area equal, at least, to the combined area of Lake Superior, Michigan and Huron, flowed south through the valley of the Minnesota River, and through the lake which then existed in a portion of that valley, into the Mississippi. The other rivers of this area while receiving considerable drainage waters from the melting ice, soon lost these waters

as the ice receded, and began to act as the drains of their present respective drainage areas.

178. **Glacial Drainage.**—The hypothetical condition of the country at one period in the recession of the glaciers is shown in Fig. 222 D. This map shows the location and outline of the southern extension of the glacial Lake Agassiz, and also the outline of glacial Lake Minnesota. The latter, while shown on the map, was probably either entirely or partially drained at this period. The glacial River Warren occupied the present valley of the Minnesota River, and to its agency the dimensions of the present valley are due. This map also illustrates the main drainage features existing at this period, at which time the glacial River Warren drained Lake Agassiz. The Illinois River drained Lake Michigan, and through the latter probably Lake Superior, Huron and Erie. At a somewhat earlier date, Lake Superior was drained through the Brule and St. Croix Rivers directly into the Mississippi, as shown by the dotted lines at the western end of the lake; but, as the glacier receded, the outlet from Au Traine Bay to Little Bay de Noquet was uncovered, and at the period illustrated by the map the outlet was probably at this point. Later the discharge probably took place across the peninsula farther to the east. It may, however, be considered doubtful whether all of the features shown in Fig. 222 D were contemporary.

At an earlier period in the recession of the ice cape the Chippewa, Black, Wisconsin, Rock and Fox Rivers had received from it a portion of their drainage waters, which had undoubtedly outlined the channels in which they now flow; but at the time illustrated in this map they had lost these waters and they carried only the flow due to the rainfall and drainage of their present drainage areas.

The vast floods from the melting ice had greatly changed the earlier glacial deposits in these valleys. The heterogeneous masses of clay, stone and sand were, in many cases, sorted, re-wrought and redeposited. As the ice further receded, the present outlet of Lake Michigan was uncovered, as was also the Hudson Bay outlet to the valley of the Red River of the North. These outlets being at lower elevation than those offered by the Illinois and Mississippi Rivers, these rivers also lost the drainage which hitherto, as the only outlets, they had been receiving from the melting ice capes. In these rivers the results due to the loss of the drainage waters were much more marked and the changes in their conditions were more radical than in the smaller rivers of this area.

179. **Post-Glacial Drainage.**—As the drainage valleys were deprived of waters from the melting ice, their carrying power decreased

and they began to build up their beds, which they had formerly excavated so as to form a valley commensurate in size and inclination with their modern capacities. The local streams, dependent only on local rainfall and drainage area, had also begun to develop as the country was uncovered by the receding ice. These in the main followed such depressions as the ice capes had formed. Rarely, if ever, in the glacial or local drainage streams, were the earlier drainage valleys closely followed throughout their entire extent. The old valleys having been filled, frequently to their tops, it was often the case that the post-glacial stream found an easier outlet from valley to valley between the hills which formerly separated valleys, than its ancient course.

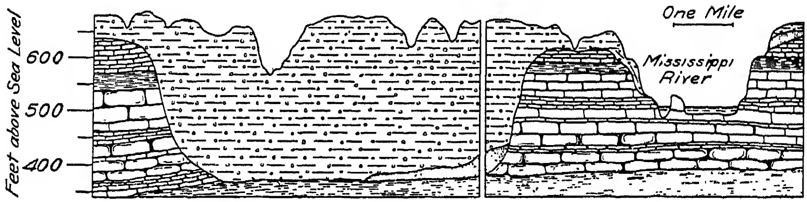


FIG 223.—Present and Preglacial Valleys of the Mississippi River near Keokuk, Iowa (Iowa Geological Survey).

As the waters cut through the drift, the rocky hillsides were frequently encountered, and these caused a diminution in the amount of cutting by the stream, while the excavation below still went on. In this way many falls and rapids have been formed both in the Mississippi River and in its tributaries. (Fig. 223, also Fig. 192, page 333.)

The drift itself, as modified by the glacial waters, possesses largely a locally developed stratification, ordinarily somewhat limited in its geographic extent.

The following sections of the drift show its variation in depth and general character, which will be seen to be subject to great local differences.

Sections of Drift.

Bloomington, McLean Co., Illinois.

Depth in feet	Material
10	Soil and brown clay
40	Blue clay
60	Gravel
13	Black mucky soil
89	Hardpan
6	Black soil
34	Blue clay
2	Quicksand
254 feet	

Minneapolis (Lakewood Cemetery).

Depth in feet	Material
135	Gravel and sand
3	Yellow clay
74	Blue till
36	Gravel and sand
8	Boulders
256 feet	

The glacial sheet, which has been described in some detail with reference to the Upper Mississippi Valley, and which was there developed perhaps to its greatest extent, extended in a broad and irrgular belt across North America from the Pacific to the Atlantic, its approximate borders being shown on Fig. 222, page 376.

Within the driftless areas, the ice floods have filled the lower valleys with detritus brought down by the flood waters, and have thus modified, although to a less extent, the topography of that region.

The major portion of the glaciated area, outside of the kettle moraine, is, however, an extended plain, modified by other morainic deposits and by drainage valleys, which have since been somewhat developed. At the close of the glacial ages the ancient topography had been destroyed and the new was in its infancy, and it is still so slightly developed that imperfect drainage is the rule on the plain between the rivers.

The common law of topographical development in the glacial area is readily understood. The circumstances of glaciation establish the limits of the drainage areas, the waters subsequently flowing from the receding ice frequently outlining the location of the streams themselves. The flood waters carve their valleys as their quantities and velocities require and gradually excavate them until their fall from source to mouth is only sufficient to cause the normal flow of their waters, carrying more or less of excavated silt in time of flood. The water has then reached its base level, and can go no lower, but works backward and forward across the valley, widening and not deepening it. The depth to which a stream can excavate its valley is then subject to the controlling features of its point of discharge, which in the case of the rivers of this region is limited by the Mississippi River and Lake Michigan. Hence, the nearer a valley is located to these outlets, the more marked is its character and depth. Few rivers in this area have reached their base level, for the time since the glacial age has been too short. The Illinoir River, in its lower course (as has been already mentioned), is an exception, the glacial waters having reduced it to a lower grade than is suitable for the discharge of its present waters laden with their normal burden of silt. Hence, the low lands are flooded and the silt is deposited, gradually raising the bed of the river; and this process if allowed to proceed unobstructed, will finally raise the lower river to its normal base level.

By such processes the surface and underlying rocks of the Upper Mississippi Valley have been formed. Volumes have been written de-

scriptive of the ages here so briefly reviewed and of the conditions which we have been obliged to pass with a glance, and to these the reader must turn for further details. Enough has been said, however, to indicate the general sequence of events and the general geological condition. For practical purposes, each district should be studied in detail and the whole subject should be examined with refence to the particular questions involved.

180. **Hydrological Conditions.**—As a source of water supply the Potsdam sandstone is one of the most important of the formations in the Upper Mississippi Valley, and its character has been examined at some length. From this source are derived numerous artesion and deep wells, which have been developed throughout the area shown on the geological map, Fig. 216, page 364.

As a source of water, the St. Peter sandstone is next in importance in this area. This deposit lies above the Potsdam, being separated from it by the Lower Magnesian limestone, and is first encountered by the drill. The elevation of its outcrop being less than that of the Potsdam, its waters have not usually as great a head and consequently it does not as often furnish flowing waters.

It has already been stated that the drift sheet which covers a large proportion of this area contains extensive deposits of sand and gravel which frequently offer available sources of water. These deposits are sometimes so extended that they may produce many of the phenomena observable in wells from the lower strata, such as artesian flows. The irregularity in the deposition of these beds of sand and gravel makes the drainage area of any particular supply almost impossible to determine. Its determination may be, however, a matter of considerable importance, especially if its source be from districts from which it may receive organic contamination.

In considering the hydrological conditions of the various strata it should be noted that all are to some extent water bearing. Even where the ratio of absorption is comparatively insignificant, the cracks and fissures often play an important part. These strata are saturated to an unknown depth, the amount of water varying with the porosity of the strata, and with their physical condition as regards cracks and fissures. This area, like many others, is marked by an alternation in the deposition of rocks varying largely in porosity, strata of high porosity frequently lying between those comparatively impervious. This variation is somewhat equalized by cracks and fissures, but the difference is still so marked as to create a great difference in the character of the flow.

The outcrop of these highly pervious strata at the higher elevations in the valley gives rise to hydrostratic pressure within the strata, a pressure which is not wholly equalized by the transfusion of waters due to porosity or to rupture. Hence, in the lower portions of the valley, these waters often come to the surface with considerable head through natural channels as springs, or through artificial channels as flowing wells.

The existence of water in the strata above renders most efficient aid in confining these lower waters of the strata. Without this their immense

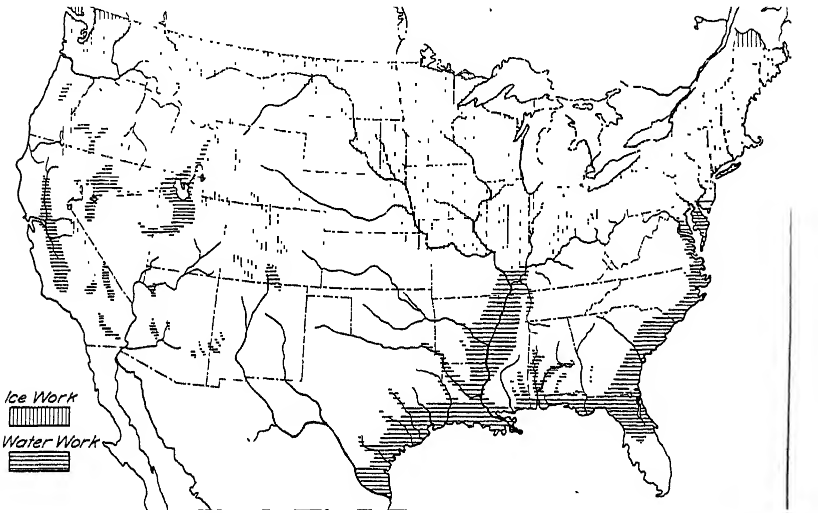


Fig. 224.—Pleistocene Deposits in the United States (see page 386).

pressures would undoubtedly bring them to the surface. Ordinarily, the difference in elevation between the head of the deeper waters and that of the ground water is very limited. At Ottawa, Illinois, however, it amounts to about 180 feet, and at Aurora, Illinois, to 90 feet.

181. **General Geology and Physiography.**—The general outline of the outcrops of geological deposits in the United States is shown in Fig. 213, page 357. A map showing approximate surface elevations of the United States is shown in Fig. 225, page 384, and a map showing approximate physiographic divisions of the United States is shown in Fig. 226, page 385. More detailed general and local maps can be found in the various publications of the United States Geological Survey and of the Geological Surveys of the various states. In the literature listed at the end of this and the previous chapter, are included only a few of the many important works to which the engineer should refer for further details on this very important subject.

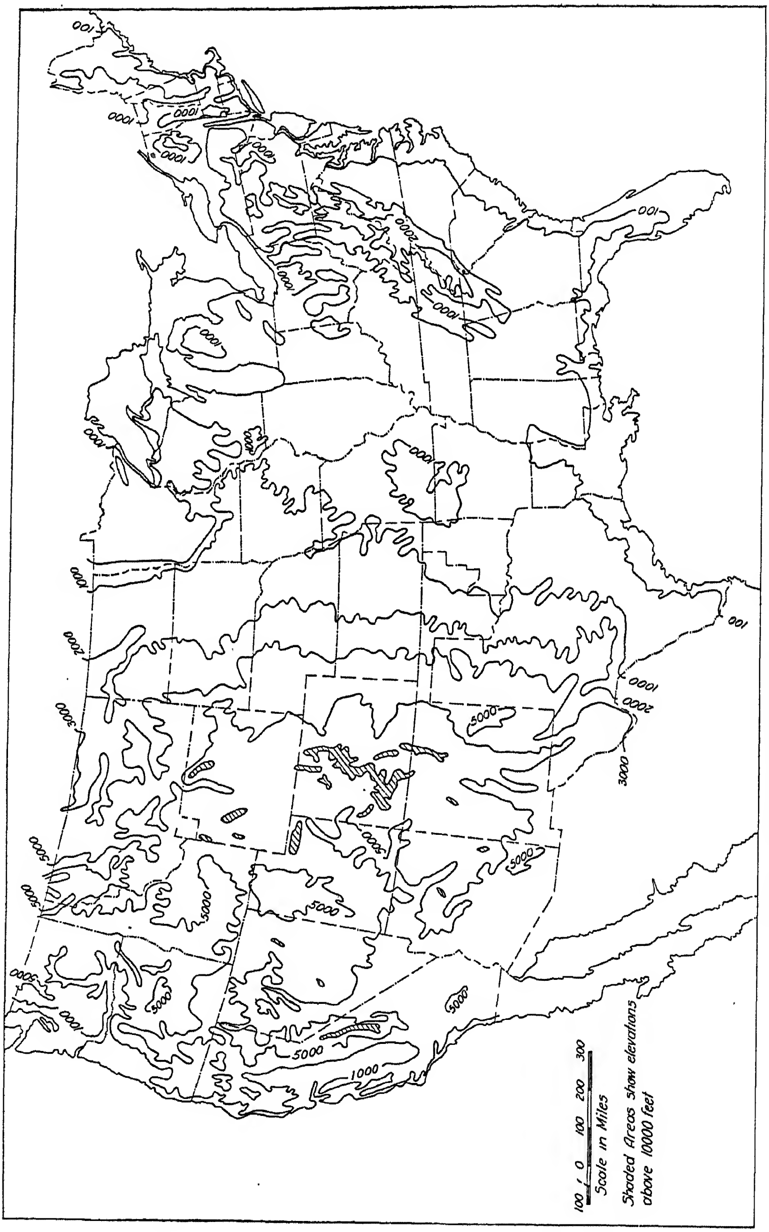


FIG. 225.—Hypsometric Map of United States (see page 383).

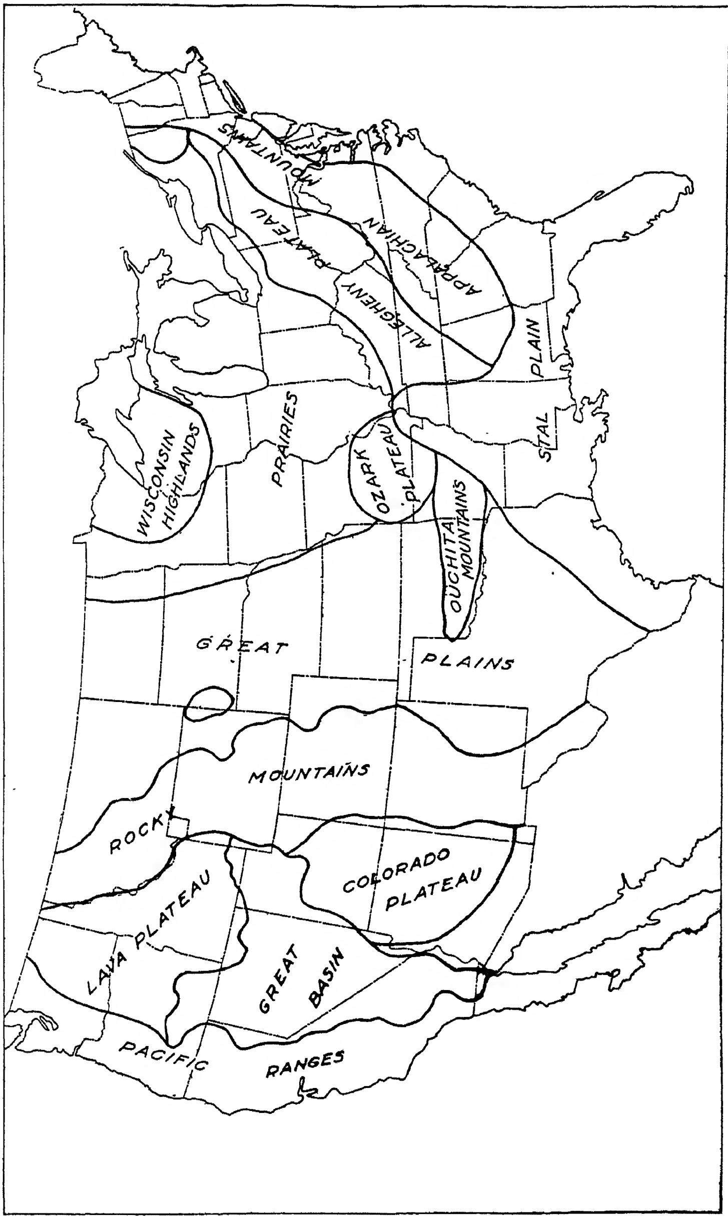


FIG. 226.—Physiographic Divisions of United States (see page 383).

Fig. 224, page 383, outlines the Pleistocene deposits of the United States which indicates that in comparatively recent geological times, the Gulf of Mexico extended above the mouth of the Ohio River, and that a broad belt of comparatively recent sedimentary deposits has been formed in the old gulf, which, as the land has gradually risen from the sea, has been pushed farther and farther to the southward, very much in the same manner that the Mississippi River is now forming new land

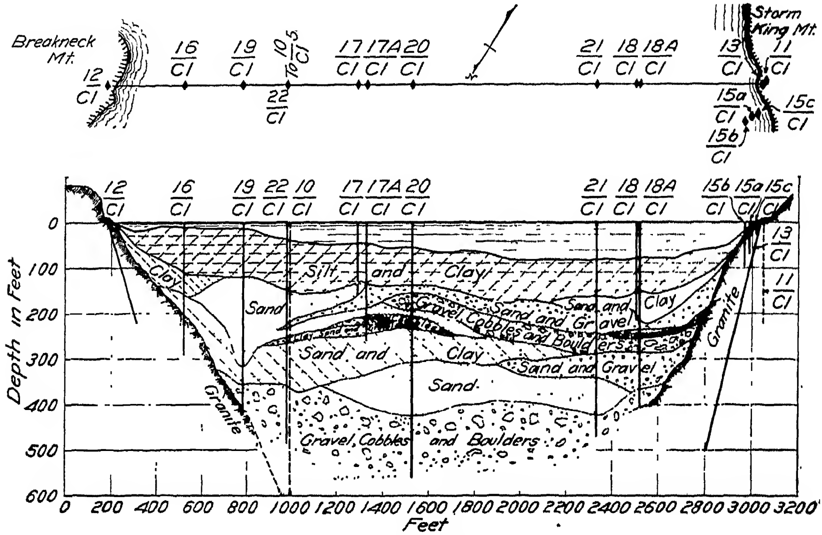


FIG. 227 A.—Plan and Profile of Storm King Crossing of the Hudson River (see page 387).

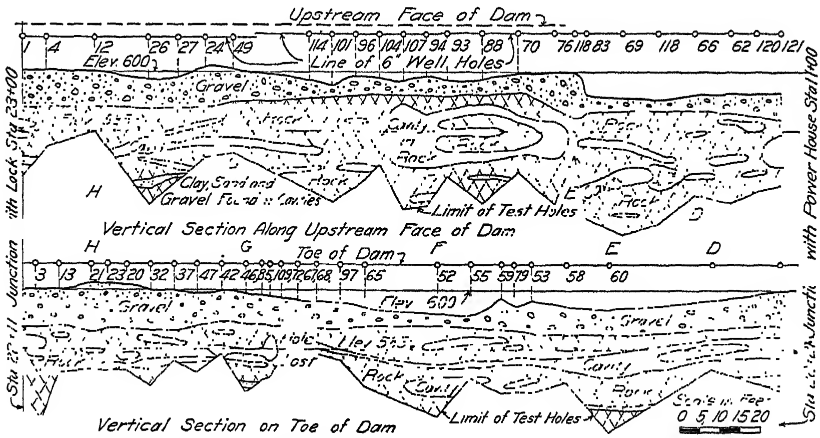


FIG. 227 B.—Plan and Profile of Borings at Hales Bar Dam (see page 387).

in the Gulf of Mexico. In this way, there has been formed the coastal plain which stretches in a broad band from Texas to Long Island, including the entire area of some of the southern states.

182. Investigation of Geological Conditions.—In the construction of dams, canals, tunnels and other structures depending upon substantial foundations for their permanency and upon the impervious structure of the underlying rocks for their safety or their success in preventing underground seepage, no work should be undertaken without exploring by excavation or borings. This is especially true within the glaciated areas and in regions where the bedrock is known to have been largely affected by diastrophic movements of considerable extent. (See Fig. 227, page 386.)

Even where the bedrocks are believed to be essentially in place, borings may develop the presence of cracks, fissures, faults or of soft or pervious strata, provision for which must be made in engineering designs in order to assure substantial and safe construction.

Too great dependence must not be placed upon a few borings especially in the drift or in règions where considerable movements have taken place, for in both cases the strata sometime vary radically within short distances, and the assumption of uniform stratification between a few borings widely separated may lead to erroneous conclusions which may seriously affect both the estimated cost and the safety of the works.[7]

The borings made for the purpose of determining the nature of underlying geological deposits also afford opportunities for hydrostratic tests to determine the porosity of the strata and their resistance to the passage of water.[8]

For the correct interpretation of the results of such borings a knowledge of the general geology of the regions is essential. In most cases where the problems involved are at all complicated, where the expense entailed in the construction is considerable or where the results entailed by a misinterpretation may be disastrous, geologists familiar with the

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7 See Catskill Water Supply of New York, by Lazarus White, Chaps. IV and V. Plate 16 shows tentative profiles as deduced from borings for Rondout Siphon and at the Kipplebush Gorge, and shows the discovery of faults and folds not previously suspected and which would not have been discovered without extended exploration work.

8 See Doc. 1202, House of Representatives, 64th Congress, 1st Session. Tennessee River between Brown's Island and Florence, Alabama (Muscle Shoals dam), page 50, Par. 36, "Pressure Tests." See also Eng. News, Vol. 75, 1916, page 1229, Investigations for Dam and Reservoir Foundations, by C. M. Saville.

local conditions, or capable of correctly interpreting the superficial geology and the data developed by the borings, should be consulted.

It is probable that if proper borings had been made, the dams at Austin, Texas,[9] and at Hales Bar on the Tennessee River [10] would not have been constructed at the sites selected, and much trouble and expense would have been avoided.

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[9] See The Austin Dam, T. U. Taylor, Water Supply Paper No. 40, 1900, U. S. Geological Survey; also Report on the Dam and Water Power Development at Austin, Texas, Daniel W. Mead, 1917, City of Austin, Publishers.

[10] Rock Grouting and Caisson Sinking for Hales Bar Dam, Eng. News, Vol. 70, 1913, pp. 949 and 1039; see also Eng. Rec. Vol. 59, 1909, p. 470 and Vol. 63, 1911, p. 641.

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CHAPTER XV

GROUND WATERS

183. The Importance of Ground Waters.—Most private and institutional water supplies, and many supplies for small towns and even for cities of considerable size such as Madison, Wisconsin; Rockford, Illinois; Memphis, Tennessee; Austin, Texas, and Savannah, Georgia are secured from underground sources. This use of ground waters for private and public supplies is due to the apparent and in most cases the actual freedom of such waters from the grosser forms of pollution and to the fact that in general more satisfactory small supplies and often more satisfactory supplies of considerable size can be obtained more readily and by less expensive means from ground than from surface waters. Ground waters commonly need no treatment to make them suitable for domestic and manufacturing uses. Such sources have also been extensively utilized for irrigation purposes and occasionally for small water powers.

The low water flow of streams is due entirely to ground waters, and conditions favorable to the storage of ground water and its delivery to the stream are essential to the maintenance of dry weather flow. In humid countries, streams that uniformly dry up in summer are those on whose drainage area there is little or no ground water storage.

The conditions which give rise to underground waters and the conditions favorable to their flow are also of importance in many hydraulic works. Conditions favorable to ground waters may add to the difficulties and expense of the construction of foundation work and may permit flows under dams and reservoir embankments and from reservoirs, canals and ditches, and thus perhaps endanger the works or at least result in a loss of water which may prove more or less serious.

Ground waters also have important relations to agriculture, and a knowledge of these relations and of the flows of water in soil is indispensable to the engineer in the proper design of drainage and irrigation works.

184. Origin and Occurrence of Ground Water.—All ground waters are derived directly or indirectly from the rainfall. The nature of the surface on which the rain falls has an important influence on its disposal. Such conditions vary from inclined impervious rock or clay surfaces, from which practically all rainfall rapidly drains away, through all va-

rieties of texture, porosity and surface covering, to horizontal, pervious beds of sand and gravel which under normal conditions imbibe all rain water received on their surface. In general, however;

1. A part of the rainfall is evaporated directly into the atmosphere.
2. A part flows directly into drainage channels as surface flow or runoff, and
3. A part seeps into the soil, subsoil and underlying strata, finally reaching an outlet in springs, streams, lakes or in the ocean.

On account of the saturated condition of the atmosphere during rainstorms, evaporation is at such times small in amount compared with that which takes place from the soil between rainstorms through capillarity and the action of vegetable life. The evaporation from soil has been discussed in Sec. 74, and Fig. 84, page 139, which illustrates evaporation under different conditions. The evaporation was calculated by deducting from the total rainfall the amounts of seepage waters collected. Fig. 228 is a direct comparison of the seepage and rainfall in these same experiments and gives some data on the amount of water which passes permanently into the ground water when the soils are well drained by underlying pervious substrata, although in the cases noted the depths of soil were not sufficient to eliminate entirely the surface evaporation losses. (See also Table 7, page 144.)

In addition to the water received directly from the rainfall it should be noted that under some circumstances the ground waters are also augmented by streams which seep into and sometimes entirely disappear in their porous beds (Fig. 232), and by the seepage of irrigation waters into the soil.

All of the materials of the earth's crust, whether loose mantle deposits or consolidated rocks, are capable of absorbing water both on account of their porous structure and by reason of cracks and fissures. The capacity for absorption varies with the porosity of the strata which in turn varies with the size and shape of the particles of which they are composed and the manner in which they are deposited. Fine material may have as great porosity as coarse material, that is the ratio of total pore space to volume of the material may be the same in two cases although the actual sizes of the interstices may be different. Different samples of the various geological deposits vary widely in porosity. The results of certain determinations of porosity measured by the percentage (in volume) of water absorbed are given in Table 38.

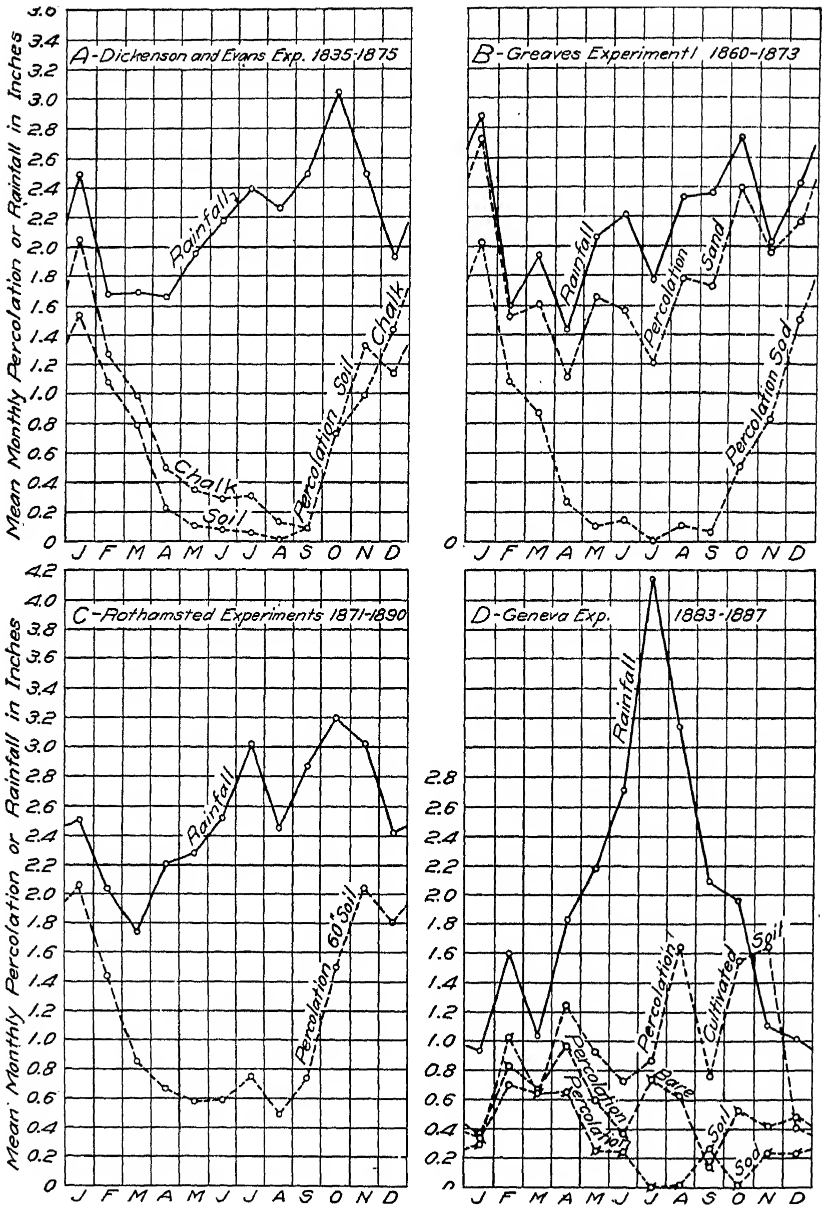

FIG. 228.—Results of Experiments on Percolation of Rainfall into Various Soils under Various Surface Conditions (see page 391).

TABLE 38.

Approximate Quantity of Water Which will be Absorbed by Soils and Rocks.

Material	Volume of Water Absorbed per 100 of Material
Sandy Soil[1]	45.4
Chalk Soil[1]	49.5
Clay[1]	50–52.7
Loam[1]	45.1–60.1
Garden Earth[1]	69.0
Coarse Sand[1]	39.4
Peat Subsoil[1]	84.0
Sand	30–40
Sandstone	5–20
Limestone and Dolomite	1–8
Chalk	6–27
Granite	03.–.8

The ground water in general saturates the strata to a depth at which the materials are so consolidated by the superincumbent weight that cracks, fissures and pores are eliminated. This depth is commonly estimated at from 6,000 to 10,000 feet but practically the ground water is confined to the upper 5,000 feet in sedimentary rocks and to about 500 feet in crystalline rocks. The strata are in general permanently saturated to the sea level near the coast and to other higher levels in the interior of the country, practically fixed by the surface of lakes, swamps or streams. From these more or less fixed water levels the water table or ground water surface slopes upward as it recedes from the point of discharge. (See Fig. 229, A.)

The saturation of the strata is not always complete. Many mines in both sedimentary and crystalline rocks are dry even far below water levels, and sandstones free from water have been encountered in deep wells.[2] The water levels of lakes and streams are in general dependent upon the ground water level. (Fig. 229, B.) If lakes or ponds are fed by streams they may seep into lower adjacent ground waters (Fig. 229, C). This condition, however, is unusual except where such bodies of water are artificial, under which conditions the lower adjacent ground water may cause considerable losses from the stored water. Occasionally reservoirs or lakes may exist above the general ground water plain without serious loss on account of the local underlying impervious strata (Fig. 229, D), and in some cases more than one water table may obtain due to local geological structure. (Fig. 229, E.) Water is en-

[1] From Geology of Soils and Substrata, H. B. Woodward, Pub. by Edward Arnold, London, 1912.

[2] W. L. Fuller, Economic Geology, Vol. 1, page 565.

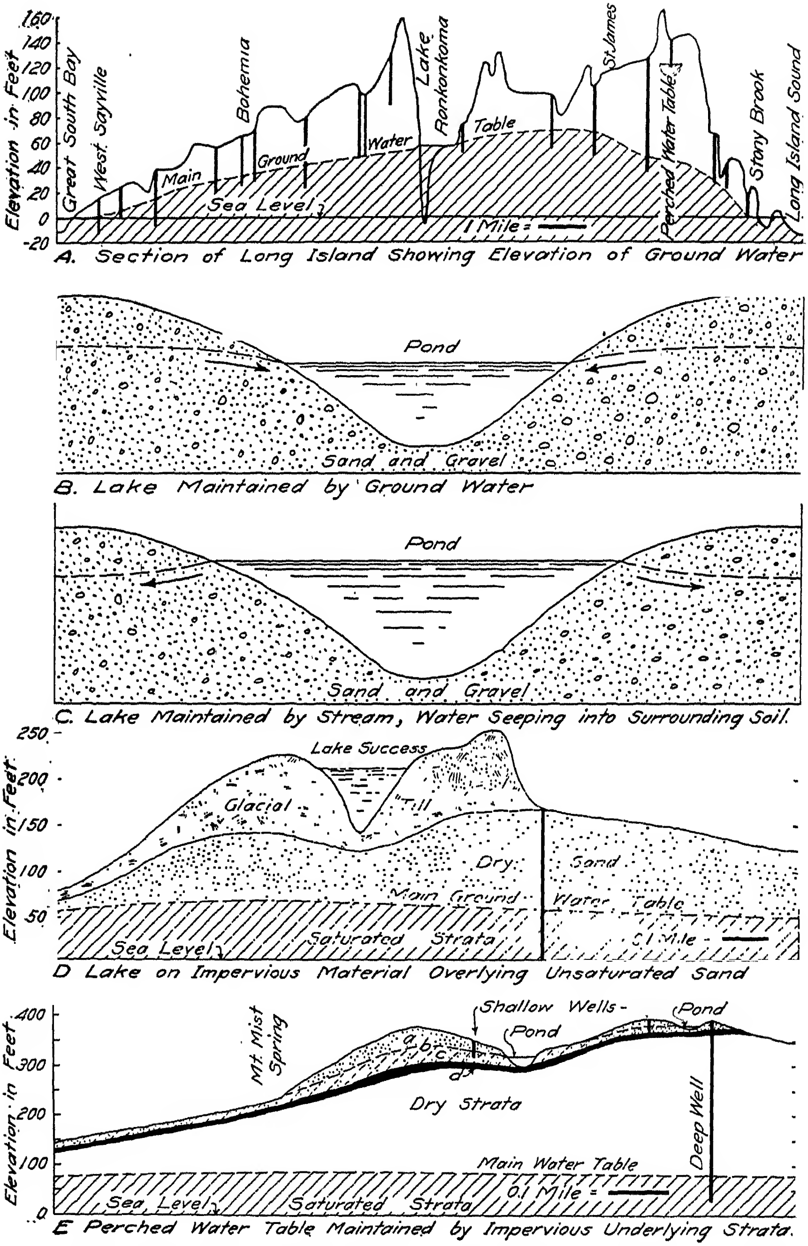

FIG. 229.—Occurrence of Ground Water under Various Conditions of Mantle Deposits.

countered in small quantities in crystalline rocks[3] and shales[4] but is found more abundantly in limestones, sandstones, and in the sands and gravels of glacial deposits and river valleys.

185. **Movements of Ground Water.**—The water absorbed by the soil passes downward, due to gravity, until it joins and modifies the surface elevation of the permanent ground water, it then seeps toward lower levels through paths of least resistance. The flow of water through the strata is governed by the same factors that control hydraulic flow in canals, pipes or other passages. (Fig. 230, A.) The size of the pores or passages in the water bearing material, the length of travel (l), the relative height of the source and point of discharge (h), and the quantity of water available result in the establishment of an hydraulic gradient (A B) and a resultant flow that remains constant only as long as the factors remain unchanged. When the ground water at the source rises (B to $B_{\prime}$) due to seepage from rainfall or other sources, the head ($h_{\prime}$), the hydraulic gradient (A $B_{\prime}$), and the flow are increased. If through lack of supply the ground water falls (B to $B_{\prime\prime}$), the head ($h_{\prime\prime}$) is decreased, and the hydraulic gradient (A $B_{\prime\prime}$) and the quantity of flow are reduced. In the same manner the flow of ground water is affected by the elevation of the surface of the body of water into which it flows. The sudden rise of a river surface (from A A to C C, Fig. 230, B) due to floods will frequently not only immediately reduce the ground water flow from that produced by the normal gradient (A B) but will often temporarily stop the flow and sometimes reverse it. In such cases the river water seeps back into the pervious banks of the stream (C D) until a new gradient (C B) is established. The tide influences the flow into the sea in the same manner and necessarily affects the elevation of the water of wells which draw their supply from the same stratum. (Fig. 230, C.) In the same way the discharge of springs and flowing wells will increase during the passage of low barometric storm areas as demonstrated by King (Fig. 230, D).[5]

The ground water surface or hydraulic gradient has a slope proportional to the resistance of the soil or rock texture to the flow and to the amount of water seeping toward the outlet. In gravels and other coarse

[3] Underground Waters in Crystalline Rocks, F. G. Clapp, Eng. Rec., Vol. 60, 1909, p. 525.

[4] Underground Waters in Slate and Shale, F. G. Clapp, Eng. Rec., Vol. 59, 1909, p. 751.

[5] See 19th Annual Report U. S. Geological Survey, 1897–98, Part 2, Principles and Conditions of the Movements of Ground Water, F. H. King; also Water Supply Paper No. 67, p. 70.

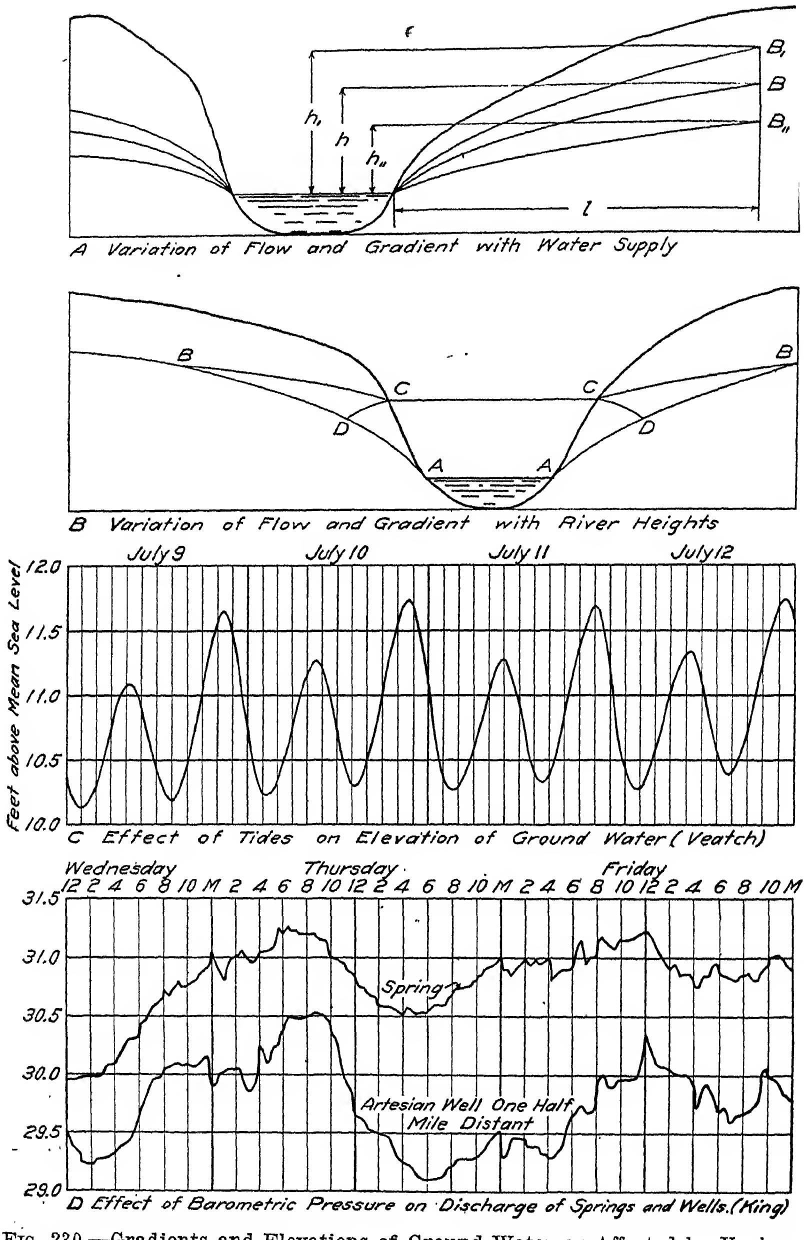

FIG. 230.—Gradients and Elevations of Ground Water as Affected by Various Conditions (see page 395).

materials the water moves freely and the inclination of the water surface is comparatively small, while in materials of close texture the gradient must be considerable to produce movement.

In their flow from the line of the drainage area to the stream the

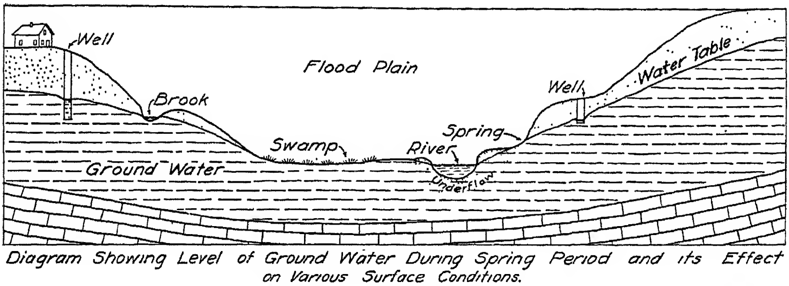

FIG. 231.—Normal Conditions of Ground Water during Wet and Dry Periods (see page 398).

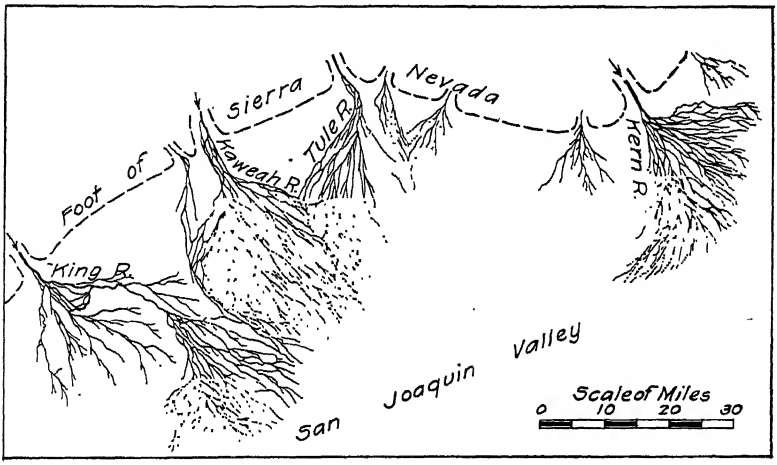

FIG. 232.—Deltas of Disappearing Streams (see page 399).

seepage waters commonly encounter differing degrees of resistance due to changes in porosity and size of soil grains even in the same stratum, hence the gradient is seldom constant except for short distances where uniform conditions prevail. Due to irregularities in surface and subsurface conditions the hydraulic gradient recedes from or approaches

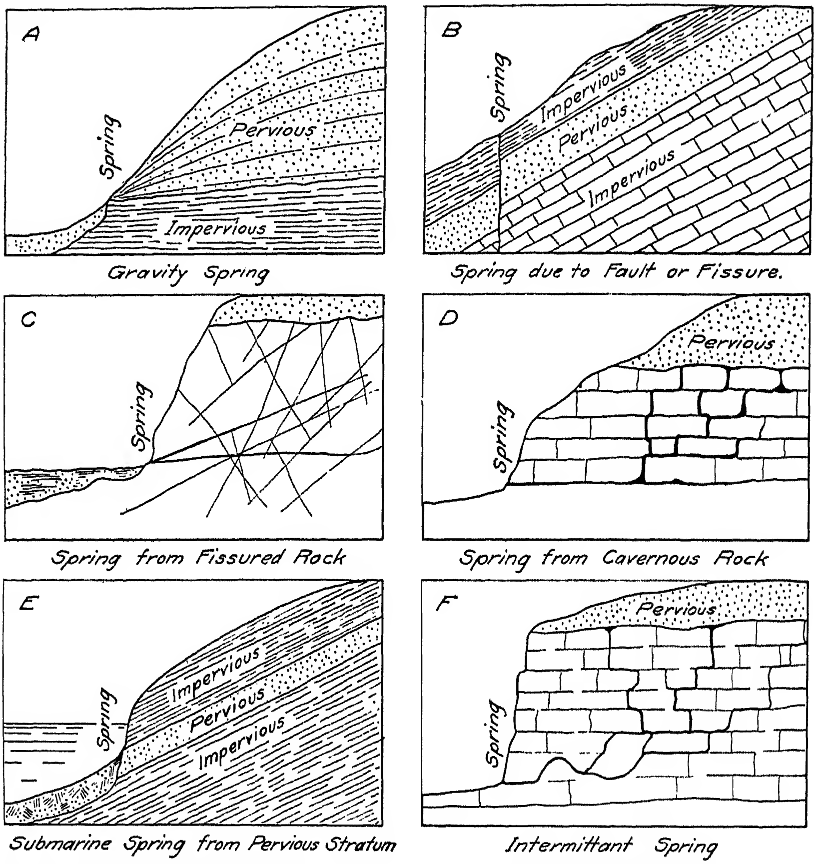

FIG. 233.—Geological Conditions which give Rise to Various Classes of Springs (see page 399).

the surface and gives rise to various phenomena illustrated in Fig. 231. When the water plain or hydraulic gradient reaches or passes above the surface the ground water causes springs, streams, lakes or swamps (Fig. 231, A), which during dry weather may become partially or entirely dried up when the water plain falls below the surface at the locality where it formerly existed. (Fig. 231, B.) In some cases the

ground water by reason of other and lower outlets may fall below the beds or adjacent streams in which case the streamflow will be decreased by seepage into its bed and banks. This is often the case in Eastern rivers when sudden floods raise the stream surface above the ground water level as noted above and is a phenomenon of common occurrence in the West where desert streams fed from the mountains flow into plains having small rainfall and low ground water. In some cases under such circumstances the streams are entirely lost by sinking into the plains after leaving their mountain channels. (See Fig. 232.)

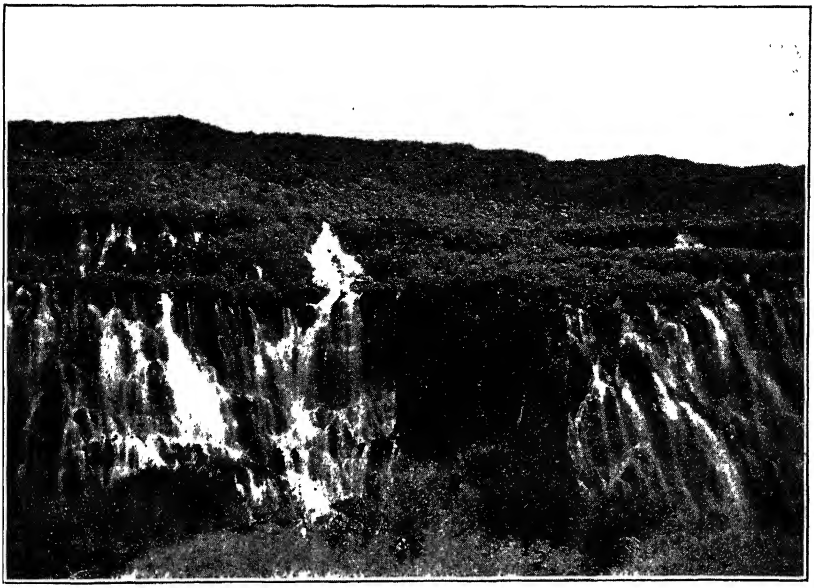

Fig. 234.—The Thousand Springs, Snake River Canyon, Idaho.

In many cases ground waters seep through pervious deposits which lie below comparatively impervious beds on which they produce an upward hydrostatic pressure due to the head at their source less the head lost by resistance of flow. Where such waters encounter cracks, fissures or wells through the overlying deposits, they rise through such openings and if the hydrostatic pressure is sufficient may appear at the surface as springs or flowing wells.

186. **Springs.**—When the hydraulic gradient of the underground water passes above the surface at any point (Fig. 231, A), and when the water bearing strata also reaches or connects with the surface, springs are formed. (Fig. 233.) Springs are sometimes produced by surface outcrops of impervious strata overlaid by pervious water bearing de-

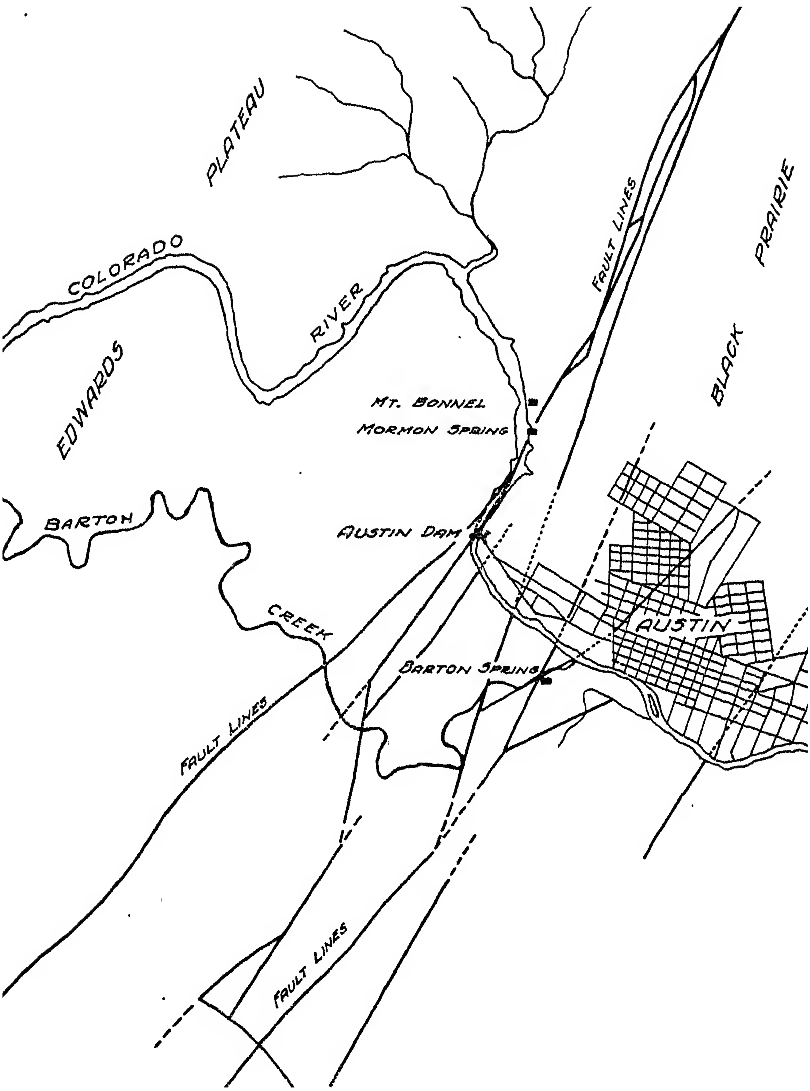

FIG. 235 A.—Fault Zone near Austin, Texas (see page 401).

posits (Fig. 233, A), or by the occurrence of surface outlets from cracked, fissured or cavernous rocks. (Fig. 233, C.) The open texture of the lava rock on the side of the Snake River Canyon in Idaho has given rise to the series of springs shown in Fig. 234. Sometimes the hydrostatic pressure raises the underground waters to the surface

through cracks, fissures or fault lines (Fig. 233, B). Springs of large capacity are often found along fault lines where the faults intersect deep lying water bearing rocks. Such a condition is found near Austin, Texas (Fig. 235), where an extensive fault zone exists. Numerous

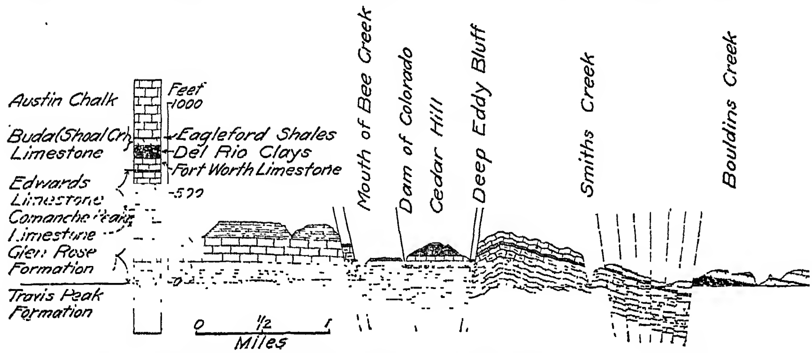

FIG. 235 B.—Geological Section Through Fault Zone near Austin, Texas.*

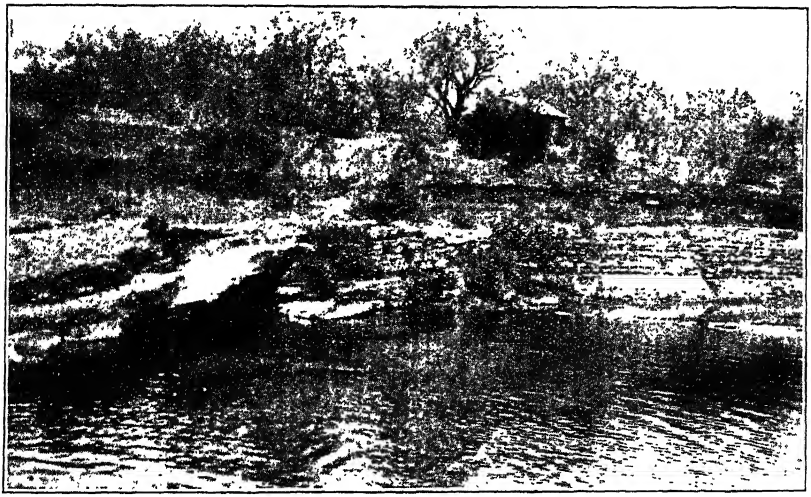

FIG. 236.—Barton Springs from Fault, Austin, Texas.

springs are found in this vicinity the largest of which is Barton Springs on the south side of the Colorado River (Fig. 236). This spring flows through fissures in the rock bed and banks of Barton Creek and has an average flow of about fifteen cubic feet per second and will probably be utilized as a water supply for the City of Austin.

The cracked, fissured and pulverized rock of one of these faults pass-

*Geologic Atlas of the U. S., Austin Folio, R. T. Hill and T. W. Vaughan, 1902.

ing under the bed of the river at the dam site above Austin was undoubtedly the cause of the failure of the dam at that place in 1900 and of much of the trouble in rebuilding that structure.[6]

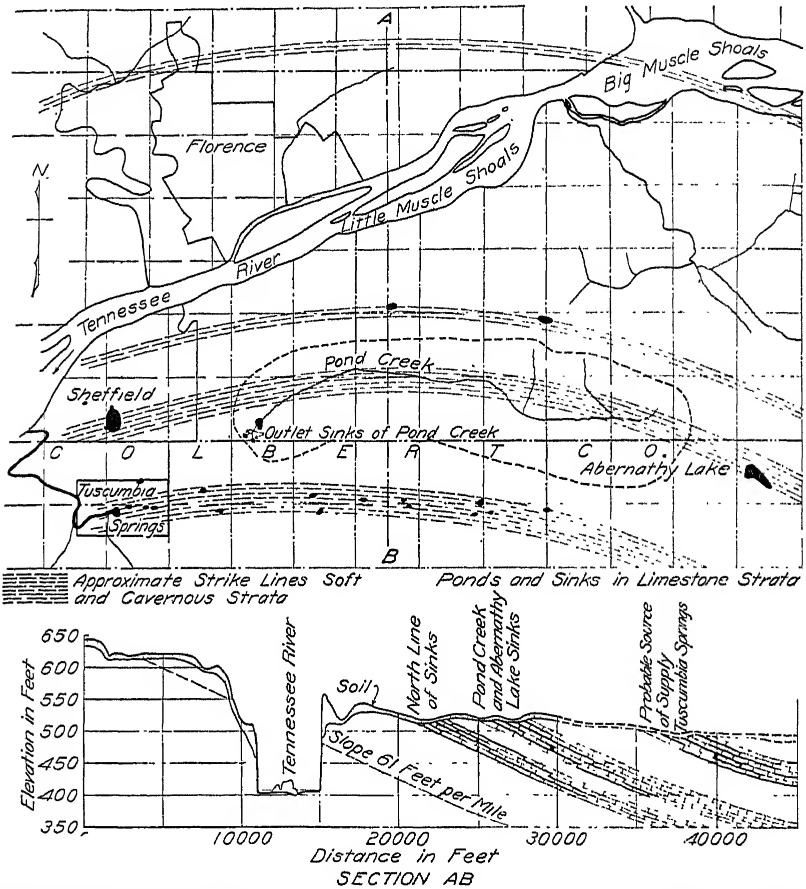

FIG. 237.—Map and Section near Sheffield, Albama, Showing Conditions which give Rise to Disappearing Streams and to Springs.

Springs often result from the flow of water through the passages in cavernous rock which outcrop at or above the surface. (Fig. 233, D.) In general, the formation of caverns by solution is limited to the rock mass above the outlet water level although the rock structure may occasionally produce lower lines of flow and consequent cavernous condi-

[6] Austin Dam, T. U. Taylor, Water Supply Paper No. 40, 1900, also Report on the Dam and Water Power Development at Austin, Texas, Daniel W. Mead, City of Austin, Publisher.

tions far below the outlet water levels. In other cases cavernous conditions may have been produced in the rocks of valleys that have later been filled with glacial, lacustrian or fluvial deposits, or disastrophic movements may have lowered the cavernous rock far below the present water plains.

Numerous springs of this class occur in most limestone regions. The exposed beds of soluble limestone in Northern Alabama near Sheffield (Fig. 237) have developed many cavernous channels. Into one of these, Pond Creek, draining about 35 miles of surface area, disappears. The

Fig. 238.—Outlet Creek from Tuscumbia Springs near Sheffield Alabama (see Fig. 237).

development of cavernous conditions in another stratum gives rise to Tuscumbia Springs (Fig. 238), one of the largest springs in Northern Alabama.

Springs from cavernous stone are sometimes intermittent on account of peculiar formations. In general, such results are produced by the formation of a collecting cavern within the rock together with a syphon outlet channel (Fig. 233, F) in which case the water begins to flow when the cavern fills to the top of the outlet channel and ceases to flow when the supply in the reservoir or cavern is exhausted, which action is repeated as the reservoir alternately fills and empties. Frequently inclined pervious strata are exposed by the erosion of the overlying rock by streams, lakes or the ocean and numerous surface and submarine springs result. (Fig. 233, E., page 398.)

187. **Artesian Conditions.**—Early wells drilled into the deep underlying strata in the Province of Artois, France, produced flowing waters at the surface. Similar conditions have since been discovered in numerous parts of the world and such conditions and the wells which develop them have been called "artesian" from the place of their first development.

In order to produce flow at the surface the hydraulic gradient of the underlying water bearing deposits must pass above the surface, otherwise the water will simply rise in the well to the local elevation of the gradient. (Fig. 239.) The term artesian is, however, commonly applied

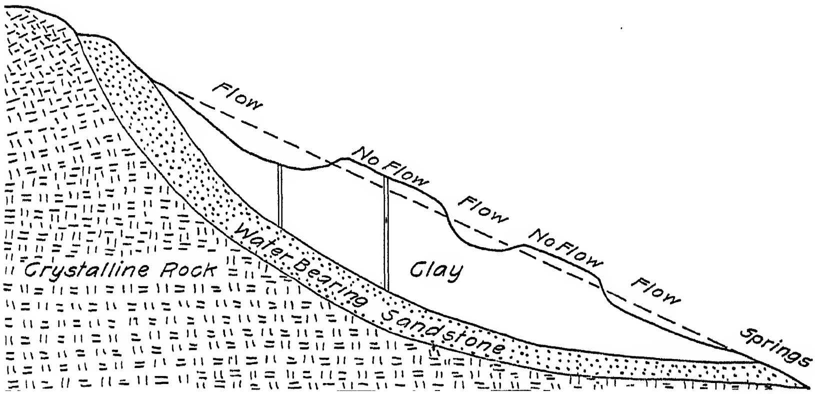

FIG. 239.—Section Showing Artesian Conditions and Relations of Flowing and Non-Flowing Wells to Hydraulic Gradient and Surface Elevation (Fuller).

to both rising and flowing wells and also to springs occurring through cracks, fissures and faults. (Fig. 233, B.)

The leading prerequisite conditions on which artesian flows depend are given by Chamberlain[7] as follows:

1. A pervious stratum to permit the entrance and the passage of the water.

2. A practically water-tight bed below to prevent the escape of the water downward.

3. A like impervious bed above to prevent escape upward, for the water, being under pressure from the fountain head, would otherwise find relief in that direction.

4. An inclination of these beds, so that the edge at which the waters enter will be higher than the surface at the well.

[7] The Requisite and Qualifying Conditions of Artesian Wells, T. C. Chamberlain, Fifth Annual Report U. S. Geological Survey, 1884, p. 131.

5. A suitable exposure of the edge of the porous stratum, so that it may take in a sufficient supply of water.

6. An adequate rainfall to furnish this supply.

7. An absence of any (easy) escape for the water at a lower level than the surface of the well.

For large flows the waterbearing material must be coarse and porous or the thickness must be great and the outcrop must be of large area and the rainfall ample.

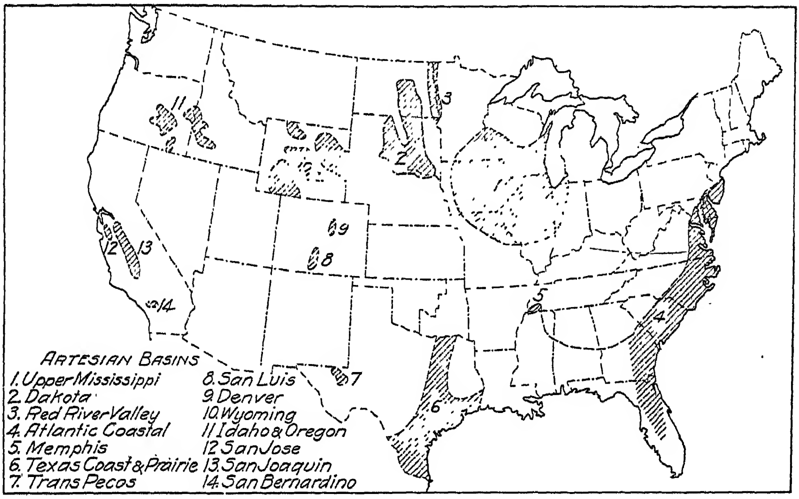

FIG. 240.—Map Showing Principal Artesian Areas of the United States.

The artesian wells of Denver formerly provided a large surface flow in the spring and early summer when the snow was melting from the foothills, but these wells decreased or ceased to flow during the dry periods of the summer. The numerous artesian wells in the Upper Mississippi Valley (for geological section see C D, Fig. 217, page 370), especially those derived from the Potsdam Sandstone show no seasonal variations in flow due to the extended outcrop of the Potsdam in Northern Wisconsin (about 14,000 square miles, see Fig. 216, page 364). The principal artesian areas in the United States are shown in Fig. 240. Geological sections which show the conditions that give rise to such wells are given in Fig. 241 for the Dakotas (A), along the Atlantic Plains (B), in Eastern Texas (C), and in the San Joaquin Valley (D). Numerous local artesian conditions are developed in the drift in Wisconsin, Illinois, Indiana and other localities, and many minor artesian

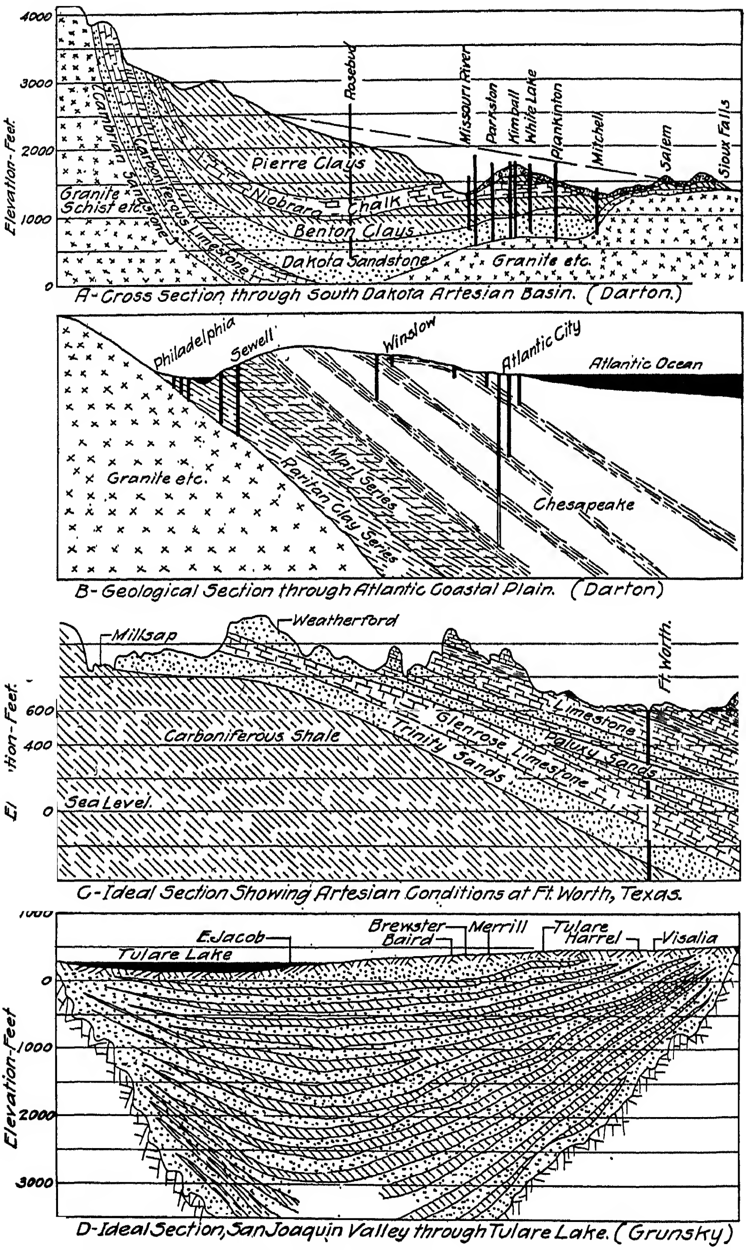

FIG. 241.—Geological Sections Showing Various Artesian Conditions in the United States (see page 405).

areas occur locally in various points of the United States, especially in the lower lands of river valleys.[8]

188. **The Underflow of Streams.**—Many streams flow over beds of sand, gravels or other pervious materials such as lacustrine deposits and

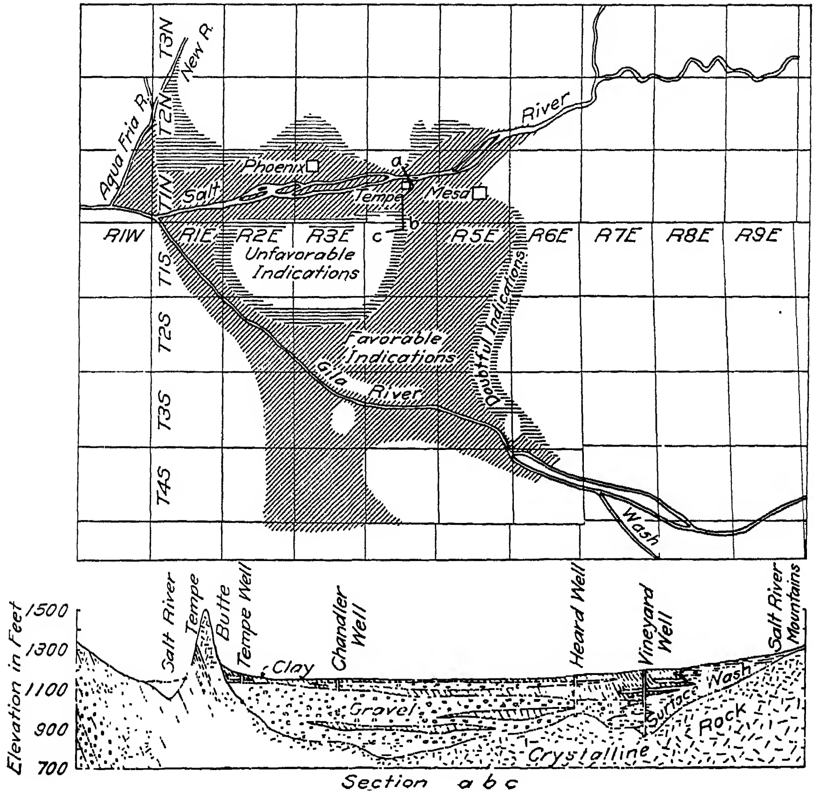

FIG. 242.—Map and Section Showing Ground Water Conditions in the Gila and Salt River Valleys. After Lee. (See page 408.)

those which have been deposited in older and deeper valleys by glacial action, by the work of former streams or by the present streams where conditions have changed their work from degradation to aggradation. These deposits are frequently very extensive and sometimes afford op-

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[8] Water Supplies of Wisconsin, S. Weidman and A. R. Schultz, Bul. No. 35, Wis. Geol. and Nat. Hist. Survey, 1915, p. 88.

The Water Resources of Illinois, Frank Leverett, 17th An. Report U. S. Geological Survey, 1895–96, Pt. 2, p. 78.

Water Resources of Indiana and Ohio, Frank Leverett, 18th An. Report U. S. Geological Survey, 1896–97, Pt. 4, p. 480.

portunities for securing abundant water supplies at points far distant from the stream channel. The underflow of the Salt and Gila River Valleys in Arizona (Fig. 242) is extensively used for the irrigation of lands both inside and outside the United States reclamation project boundaries, some of these wells furnishing (by means of pumps) supplies of four cubic feet per second (Fig. 243). Many supplies of cities

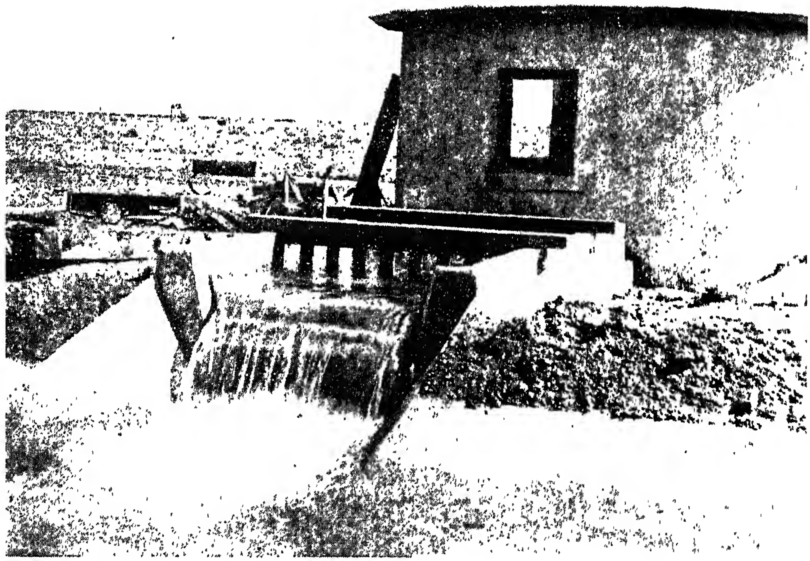

Fig. 243.—One of the Wells of the Southwestern Cotton Company in the Gila Valley. Four Cubic feet per Second Pumped from Ground Water.

are taken from similar sources. The water supply of Wichita, Kansas, is derived from the underflow of the Arkansas River and provides an adequate amount of water for that city when the river bed is dry and the ground water surface of the underflow is drawn down several feet below the river bed. (Fig. 244.) In many cases where the old stream valleys are filled with sands and gravels, the presence or absence of streamflow is simply a question of the elevation of the general ground water gradient above or below the stream bed. In other cases, when the present beds are more or less impervious, the streamflow and the underflow are independent both in character and direction of flow.

189. **Temperature of Ground Waters.**—It has been shown (see Fig. 14, page 48) that the temperature of the earth below the surface is not subject to as great a range of temperatures as air or surface waters. In consequence of this even the higher ground waters are comparativly cool in summer and warm in winter. There is also a considerable increase in temperature from the surface downward amounting in general to about one degree for each 50 to 100 feet. The U. S. Geological Survey measured the temperature in the deep well at Wheeling, West Virginia with the results shown in Table 39.

FIG. 244.—Sand Bed of the Arkansas River at Wichita, Kansas, during Lo Water (see page 408).

TABLE 39.

Underground Temperatures at Different Depths in the Well at Wheeling, West Virginia.

Depth Feet	Temperature Fahr. Degrees	Depth Feet	Temperature Fahr. Degrees
100	51.30	2,990	86.60
1,350	68.75	3,125	88.40
1,591	70.15	3,232	89.75
1,592	70.25	3,375	92.10
1,745	71.70	3,482	93.60
1,835	72.80	3,625	96.10
2,125	76.25	3,730	97.55
2,236	77.40	3,875	100.05
2,375	79.20	3,980	101.75
2,436	80.50	4,125	104.10
2,625	82.20	4,200	105.55
2,740	83.65	4,575	108.40
2,875	85.5	4,462	110.15

These temperatures may be compared with those of the deep well near Berlin, Germany, which is 4170 feet in depth and has a surface temperature of 47.8° and a bottom temperature of 118.6°, and with the well at Leipsig, Germany, 5,740 feet deep with temperatures at the top

TABLE 40.

Temperatures of Deep Well Waters.

Location of Well	Depth of Well	Temperature Degrees F.	Reference
Rockford, Ill.	1320 to 1996	60	....
Galena, Ill.	1509	49	....
Oak Park, Ill.	2780	64	....
Ellendale, N. D.	1087	67	Eng. News, Vol. 21, 1889, p. 326,
Redfield, S. D.	960	68	Eng. News, Vol. 21, 1889.
Huron, S. D.	863	60	
Yankton, S. D.	600	62	
Jamestown, N. D.	1576	75	
St. Augustine, Fla.	1400	86	Eng. News, Vol. 27, 1892.
Alamosa, Colo.	1000	75	U. S. G. S. Water Supply Paper 57.
Canon City, Colo.	1600	90	
Denver, Colo.	500	50	
Denver, Colo.	350	56	
Guntersville, Ala.	1006	60	
Arkansas City. Ark.	552	72	
Loyalton, Cal.	1000	130	
Santa Clara, Cal.	600	60	
Oglethorpe, Ga.	490	62	
Keokuk, Ia.	2000	65	
Richfield, Kan.	370	66	
Louisville, Ky.	1900	57	
Elkton, Md.	490	45	
New Orleans, La.	1200	68	
Alpena, Mich.	650	52	
Winona, Minn.	478	54	
Scranton, Miss.	774	74	
Louisiana, Mo.	1275	64	
Miles City, Mont.	456	57	
Omaha, Neb.	1065	62	U. S. G. S. Water Supply Paper 61.
Sierra Valley, Nev.	1132	Hot	
Longport, N. J.	803	66	
Ashland, Pa.	1830	54	
Charleston, S. C.	1970	99.5	
Knoxville, Tenn.	2100	57	
Ft. Worth, Tex.	3250	140	
Galveston, Tex.	1365	84	
Reedville, Va.	680	78	
N. Yakima, Wash.	650	71	
Green Bay, Wis.	950	53	

and bottom of 51.9° and 135.5° respectively. On account of these conditions deep well waters are usually much warmer than the shallower ground waters, as shown in Table 40.

In certain regions thermal springs are found which are sometimes of boiling temperatures. Some of these derive their temperature from the great depths to which the seepage waters have previously percolated through fissures. In other cases the waters are heated by chemical action, while in volcanic regions waters are heated to high temperatures at comparatively shallow depths by the presence of uncooled lava. There are about 3,000 springs of this latter class in Yellowstone National Park.

TABLE 41.

Qualities of Water Collected During a Rainstorm at Rothamsted, England.[9]
(Parts per million)

Time of Collection	Total Solids	Carbon in Organic Matter	Nitrogen as Organic Matter	Nitrogen as Ammonia	Nitrogen as Nitrites and Nitrates	Nitrogen as Total Nitrogen	Chlorine
3:00 P. M.	40.8	0.93	0.18	1.07	0.18	1.43	1.0
4:30 P. M.	29.4	0.62	0.19	0.37	0.13	0.69	0.8

190. **The Qualities of Ground Water.**—No water is found in a state of chemical purity in nature. The rain falling through the atmosphere takes up various floating matters and absorbs various gases from the air. Its quality improves in the later part of the storm after the air has been partially cleansed by the earlier rainfall. (See Table 41.)

When it reaches the ground, the rain water as it runs over the surface dissolves, erodes and carries away in solution and in suspension some of the various materials with which it comes in contact. In this way the streams receive the washings from farm yards and fields and carry away silt, sand and organic matter to the rivers and the sea. In the same manner the water also carries similar matter into cracks and fissures of the rock, but as it seeps into the soil and sand, the coarser materials in suspension are left on the surface and only the finer organic and mineral matter and the matter in solution are carried into the ground. As the water flows through the soil and underlying forma-

[9] Journal of the Royal Agricultural Society, 1847, p. 257.

tions, the matter in suspension is rapidly removed if the strata are fine material, but the moving water constantly adds to its burden of matter in solution and becomes more highly mineralized the more soluble the

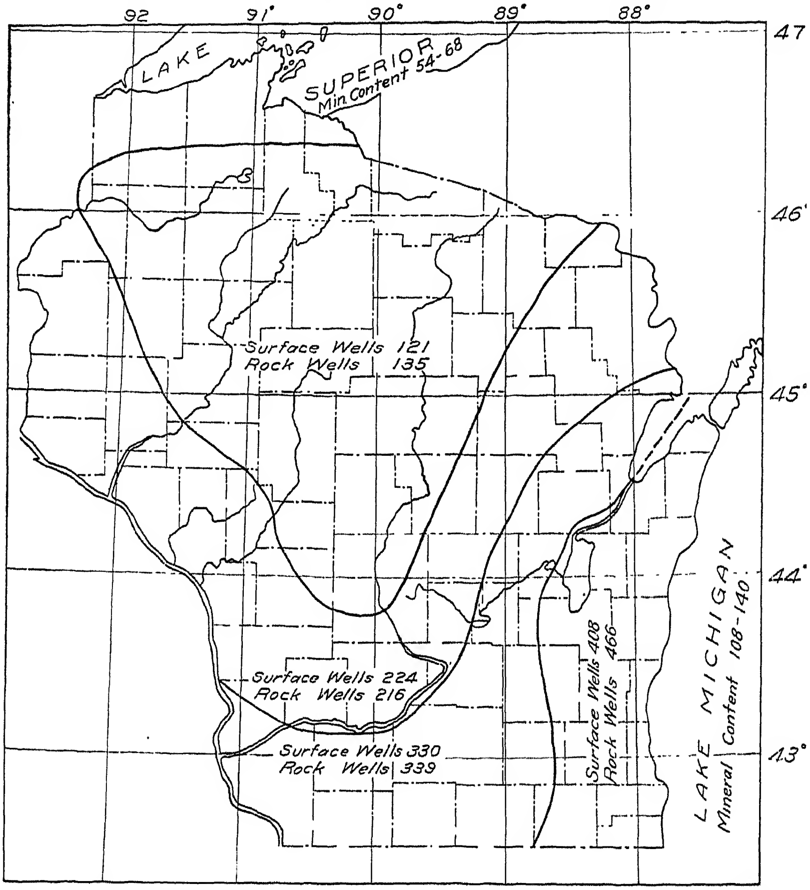

FIG. 245.—Average Mineral Content in Parts per Million of Surface and Rock Wells in Wisconsin. After Weidman and Schultz.

material of the strata with which it comes in contact and the longer and farther it flows.

Water from the cracks and fissures of the comparatively insoluble crystalline rocks contains only a small amount of matter in solution and is termed "soft water." The mantle and sedimentary rocks contain much soluble matter and the waters from such deposits are more highly mineralized the farther they are found from their source. As in general the deeper rocks in any section appear at the surface and absorb the

rainfall at a greater distance from that section, the deep waters are in general more highly mineralized than those from lesser depths. The progressive increase in mineral content of the ground water in proportion to the depth and travel is shown in the map (Fig. 245) and section (Fig. 246) of Wisconsin, and in Table 42 which includes also the deeper waters of Iowa.[10] In Iowa deep wells are defined as those more than 700 feet in depth.

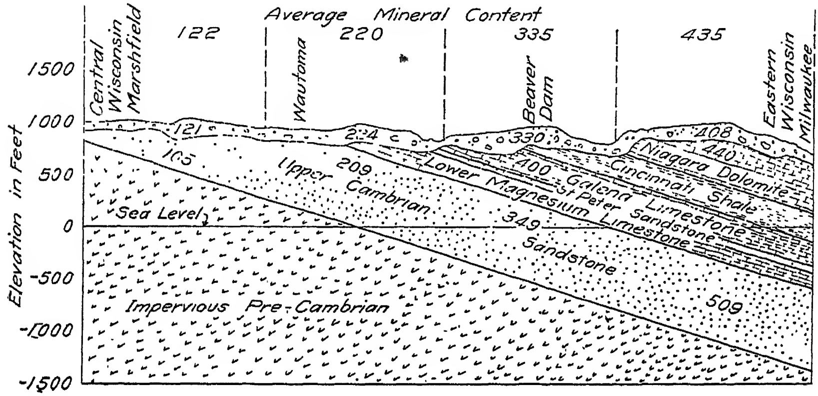

Fig. 246.—Geological Section through Wisconsin and Average Mineral Content of Surface and Rock Wells. After Weidman and Schultz.

TABLE 42.

Showing the Relation of Depth to Mineralization of Underground Water in Wisconsin and Iowa.

District	Approximate Depth of Underground Water or Thickness of the Water-bearing Strata	Average Mineral Content in Parts per Million	
Central Wisconsin	100 to 200 Feet...	Surface Deposit Wells	121
		Rock Wells	135
Western Wisconsin	400 to 800 Feet...	Surface Deposit Wells	224
		Rock Wells	216
Southwestern Wisconsin ..	800 to 1600 Feet...	Surface Deposit Wells	330
		Rock Wells	339
Northeastern Iowa	1600 to 2000 Feet...	Shallow Wells	388
		Deep Wells	351
Central Iowa	About 3000 Feet...	Shallow Wells	873
		Deep Wells	1759
South Central and Southwestern Iowa	About 4000 Feet...	Shallow Wells	1587
		Deep Wells	3657

[10] Water Supplies of Wisconsin, by Samuel W. Weidman and A. R. Schultz.

The character of the mineral content of underground waters depends entirely upon the chemical character of the strata through which they flow. (See Table 43.) The waters of the Potsdam Sandstone of the Upper Mississippi Valley (see Table 44) are more largely charged with the bicarbonates of lime, soda and magnesia, with minor quantities of

TABLE 43.

Analysis of Residues of Various Spring Waters in the Upper Mississippi Valley, Grams per U. S. Gallon.

Compound	Elgin, Ill. Zoman Spring	Cook Co., Ill. Glen Flora Spring	St. Croix, Wis. Mineral Spring [a]	Waukesha, Wis. Hygeia Spring	Owatonna, Minn. Vichy Spring
Potassium Sulphate	....	....	....	.69	.28
Sodium Sulphate	1.75	1.85	.52	....	.45
Potassium Carbonate	....	....	....	....	....
Sodium Chloride	.71	.18	.05	1.89	.34
Sodium Carbonate	.46	6.45	.79	....	52.41
Magnesium Sulphate	....	....	....	4.04	....
Magnesium Bicarbonate	....	11.09	7.25	4.63	8.40
Magnesium Carbonate	2.50	....	....	.21	....
Calcium Bicarbonate	....	15.57	11.19	19.23	16.37
Calcium Carbonate	9.57	....	....	....	....
Calcium Sulphate	....	....	....	1.62	....
Ferrous Bicarbonate	....	....	....	.01	.54
Ferrous Carbonate	.50	.11	} .49	} 3.04	....
Alumina Carbonate	} .27	.15			.10
Silica		.91	.27	.71	1.79
Free Carbon Dioxide	....	....	1.43	1.43	4.34
Total grains per Gallon	15.76	36.31	20.56	37.50	85.02

[a] Spring from Potsdam Strata.

sodium chloride and occasionally with many other salts. The waters from limestone regions commonly contain carbonates of lime and magnesia with various other salts. On account of the mineral content of ground waters, the consequent flow of streams is much harder during low water periods than during high water when the flow is derived largely from surface runoff.

In the desert regions of the West the soils contain greater proportions of the alkaline salts which are detrimental to vegetation. Waters from such strata, when they rise to the surface or when they stand on the surface and evaporate, leave behind an alkaline residue which prevents the growth of vegetation and spoils the land for agricultural purposes until

it is properly drained and the deposited salts are dissolved and carried away by the proper application of irrigation waters.

Waters from underground sources which in general are more highly mineralized than surface waters are as a rule free from the grosser forms of pollution often found in surface streams. The soil and mantle

TABLE 44.

Mineral Character of Waters from Sandstones at Various Places in the Upper Mississippi Valley, Grams per U. S. Gallon.

Compound	Jersey-ville, Ill. Water Works Well	Mon-mouth, Ill. Water Works Well	Dekalb, Ill. Water Works Well	Rock-ford, Ill. Water Works Well	Mad-ison, Wis. Water Works Well	Sheboy-gan, Wis. Public Well
Potassiun Sulphate	10.30	4.86	1.13	.50	.24	....
Sodium Sulphate	5.05	23.45		.36	.29	....
Potassium Chloride	....	....	.11	....	....	14.48
Sodium Chloride	85.93	9.61		.27	.29	306.94
Sodium Phosphate	Trace	....	....	Trace	Trace	....
Magnesium Bicarbonate	15.53	14.07	6.47	12.80	12.89	.17
Magnesium Chloride	....	....	....	....	....	54.91
Calcium Chloride	....	....	....	....	....	27.82
Calcium Bicarbonate	6.84	15.82	8.39	13.17	15.24	13.66
Calcium Sulphate	16.91	4.70	....	....	....	169.83
Ferrous Bicarbonate	.11	.24	.69	.08	.21	.50
Alumina	.06	.10		.14	Trace	.13
Silica	.78	1.04	......	.58	....	.47
Sodium Bicarbonate	....	....	.70[a]	.82	1.09	.33[b]
Totals	141.51	73.89	17.49	28.72	30.25	589.24

[a] Organic.

[b] Composed of chlorides of lithium, bromide of sodium and phosphates of line, with trace of soda, sulphate of baryta and bicarborate of soda.

deposits undoubtedly have a purifying effect on polluted waters both by straining action and by the activity of nitrifying organisms in the upper soil. Nevertheless, the waters of many shallow wells are frequently grossly polluted by seepage from nearby vaults, cesspools and barnyards (Fig. 247), and often deep wells are polluted in the same manner by improper casing through the mantle deposits. Springs and deep wells are also sometimes polluted by the passage of organic matter through open and cavernous formations (Fig. 248). Such pollution is of a most dangerous character because its existence is unseen and unrealized, and the clear and sparkling waters seldom give apparent evidence of their dangerous condition.

191. Velocities and Quantities of Ground Water Flow.—In many places where ancient river valleys are filled with great deposits of sand and gravel there are extensive ground waters from which large supplies are sometimes obtained. (See Fig. 243.) The general public and

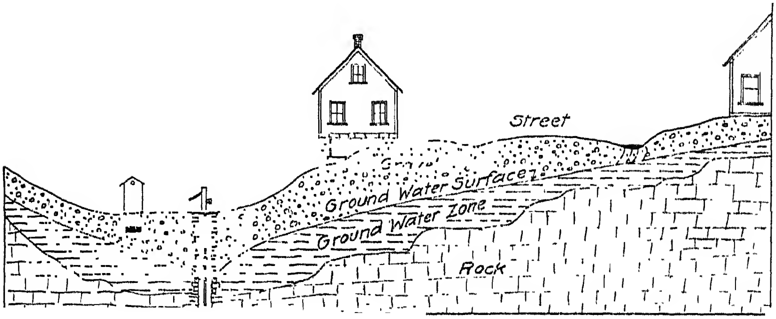

FIG. 247.—Pollution of Wells from Surface Drainage of Streets and Seepage from Vaults (see page 415).

sometimes engineers, in making estimates of the quantities that can be obtained from such sources, are misled by the large volume of water present in these deposits. The movement of such ground waters under their normal gradient is very low (see Table 45), and to secure a large

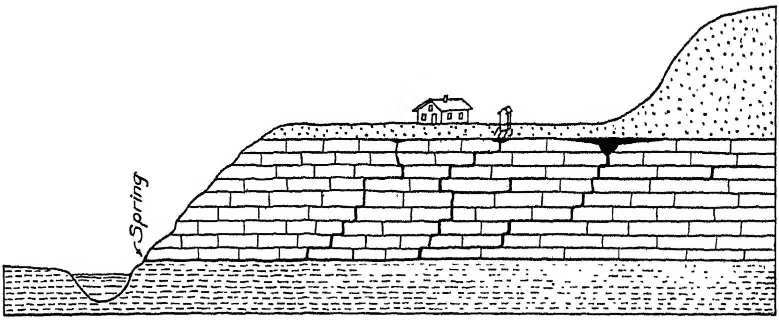

FIG. 248.—Pollution of Spring from Surface and Subsurface Drainage (see page 415).

quantity of water from wells, filters, galleries, etc., a considerable depression must be created in the ground water plain in order to produce the comparatively large head necessary to increase the velocity and induce the desired flow.

In the spring of 1918 such a source was proposed as a water supply for a large irrigation project in a Western state. During the spring and fall water is available from a stream which, however, becomes dry

TABLE 45.

Results of Some Observations on the Flow of Ground Water.

Locality	Material	Gradient Feet per Mile	Rate Feet per Day	Authority	Reference
Dakota	Sandstone	....	14.5–29.0	Darton	18th Ann. Rep. U. S. G. S., pt. IV, 1896-7, p. 609.
....	Average Sand	....	14.5	E. L. Rogers	Eng. Rec., Vol. 25, 1892, p. 435.
Rio Hondo, Cal. } San Gabriel River, Cal. }	Aluvial	....	1.17–58.0	Slichter	U. S. G. S., W. S. Paper No. 140, 1905.
Mojave River, Cal.	Gravel	20.	9.0–96.0	Slichter	U. S. G. S., W. S. Paper No. 140, 1905.
Long Island	Coarse Sand	10–12	0.2–12.0	Slichter	U. S. G. S., W. S. Paper No. 140, 1905.
Wantagh Res.	Sand	....	10.6–96.0	Slichter	U. S. G. S., Prof. Paper No. 44, 1906.
....	....	7.0	2.6	Slichter	U. S. G. S., Prof. Paper No. 44, 1906.
East Meadow Pond	Fine Sand	17.0	5.4	Slichter	U. S. G. S., Prof. Paper No. 44, 1906.
Arkansas River	Fine Gravel	7.9	7.4	Slichter	U. S. G. S., W. S. Paper No. 153, 1906.
Ogalalla, Kan.	S. Platte Gravel	....	6.4	Slichter	U. S. G. S., W. S. Paper No. 181, 1906.
Rillito Valley	Sand	23.8	33.0–274.0	G. E. P. Smith	Agric. Exp. Sta., Univ. Ariz., Bul. 64, 1910.
Rillito Valley	Sand and Silt	25.4	13.0– 60.0	G. E. P. Smith	Agric. Exp. Sta., Univ. Ariz., Bul. 64, 1910.
Rillito Valley	....	23.8	17.0– 96.0	G. E. P. Smith	Agric. Exp. Sta., Univ. Ariz., Bul. 64, 1910.
....	Coarse Sand	....	12.0– 23.0	Slichter	U. S. G. S., W. S. Paper No. 110, 1904.
Los Angeles River	Silt and Sand	....	3.4– 27.0	Hamlin	U. S. G. S., W. S. Paper No. 112, 1905.
Los Angeles River	Fine Sand	....	7.0– 77.0	Hamlin	U. S. G. S., W. S. Paper No. 112, 1905.
Los Angeles River	Gravel	....	3.4– 96.0	Hamlin	U. S. G. S., W. S. Paper No. 112, 1905.
Los Angeles River	Coarse Sand	....	2.5– 6.4	Hamlin	U. S. G. S., W. S. Paper No. 112, 1905.

for about six months during the principal irrigation season, and during this time water to the amount of 750 cubic feet per second would have to be obtained, if at all, from the ground water which in the upper valley is contained in coarse sand and gravels several miles in width and several hundred feet in depth, and from which large supplies are obtained from wells. The underflow at the outlet of the valley passes through the section shown in Fig. 249, with an area above the rock bed and below the stream bed of 50,000 square feet. Five thousand square feet of this is fine sand and silt, and 45,000 square feet is coarse sand

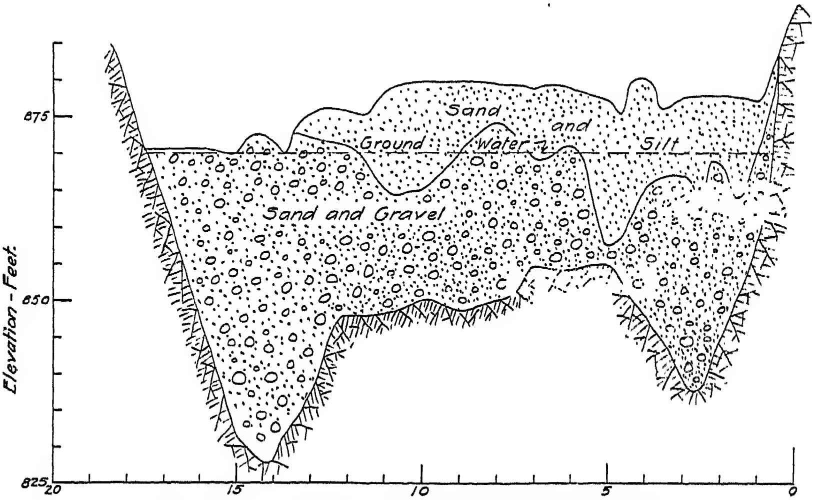

FIG. 249.—Underflow Section of a Western River.

and gravel. The ground water above this section has a slope toward the outlet of nine feet per mile. The project involved an expenditure of about $2,000,000 and promised a large profit if the ground water supply was dependable. The engineer of the project reported that a sufficient supply could be obtained from this source. Was he correct? An investigation of the probable flow in this cross section as shown, and on the assumption of the section being entirely filled with sands and gravels of various degrees of coarseness and with other ground water slopes, will furnish a point to the following discussion and show how important the subject of ground water flow may become under certain conditions.

In investigating the flow of water through sand, experiments have been made on materials which could be examined, weighed, measured, and the porosity of which could be determined by various methods which the experimenter applied. Even under such conditions it has been found that the accurate determination of porosity and the effective

size of the material are attained only by careful manipulation, and that where crude methods are applied to such measurements very discordant results are obtained.

In the formulas derived from the experiments of Hazen[11] and Slichter,[12] an "effective size" of sand or soil grains, expressed in millimeters, is used to define the comparative coarseness of the material; but each experimenter determined this by a different method, and there is no known basis of comparison between them. These formulas are inapplicable unless "effective size" of the material and other factors are determined in the same manner and with the same degree of care and skill as in the case of the original experiments, and even then they will apply only to conditions of uniformity and kind of material used in the original experiments and which can be found only under experimental conditions.[13]

The general principles that underlie the flow of ground water through porous soils are as follows: The velocity of flow will

1. Increase directly with the head or difference in elevations between the water at the inlet and outlet of the column of soil.

2. Decrease directly with the length of travel through the column of soil considered.

3. Increase rapidly with the size of the pores of the water bearing material.

4. Increase rapidly with the porosity or percentage of voids in the water bearing material.

5. Increase with the temperature of the flowing water.

Darcy,[14] who made the first attempt to investigate this subject, pointed

[11] Annual Report Mass. State Board of Health, 1892, p. 541. Some Physical Properties of Sands and Gravels with Special Reference to Their Use in Filtration, Allen Hazen.

NOTE—Mr. Hazen has called attention to the purpose of these investigations and cautioned against the use of his formula under conditions foreign to those from which it was derived. See A. S. C. E., Vol. 73, p. 199.

[12] Nineteenth Annual Report U. S. Geological Survey, 1897–98, Pt. 2, C. S. Slichter, Theoretical Investigations of the Motion of Ground Water; also Water Supply Paper No. 67, C. S. Slichter, The Motion of Underground Water.

[13] When the problem of the engineer is such that the size of grains and character of the material can be determined (as in flow through filter sands) he should refer to the original discussion of this subject as a basis for his calculations for information concerning methods of determining porosity and effective size.

[14] Les fontanies publiques de la ville de Dijoin H. Darcy, 1856, Paris.

out that the velocity of flow through soil is directly proportional to the head and inversely proportional to the length of flow; that is

$$v = k\frac{h}{l} \tag{1}$$

Where

v = Velocity of flow (in feet per minute)
h = Head acting on the soil section (in feet)
l = Length of the column or soil section (in feet)
k = A factor of flow to be determined experimentally for each material

Slichter's formula for estimating the flow of water through a column of sand is as follows:

$$q = 0.2012\frac{hd^2a}{\mu lK} \tag{2}$$

in which

q = Quantity of water transmitted by the column per minute
h = The head producing the flow (in feet)
a = Area of the cross section of the sand bed (in square feet)
l = Length of travel of the water
d = The effective diameter or effective size of the sand grains
μ = A viscosity coefficient (which decreases rapidly with an increase in temperature)
K = Porosity coefficient (varying with porosities of from 20 to 47 per cent)

The part of the expression varying with the character of the soil may be represented by a coefficient or transmission constant, k, when Equation 2 becomes

$$q = k\frac{ha}{l} \tag{3}$$

which is essentially the same as the formula of Darcy.

As has previously been noted, the formulas of the type of Equation 2 for the flow of water through sand, etc., are all dependent upon the accurate determination of porosity and effective size of the porous medium. This effective size is dependent on the nature of about ten per cent. of the finest material, and there is no method uniformly applicable by which this effective size can be accurately determined for all classes of material. Even the porosity of a fine material cannot be determined without great care, for this factor depends not only on the size and shape of the grains but on the method of packing as well, and a removal of samples from a natural bed will alter their arrangement and may affect the porosity.

In estimating the flow of ground waters both the porosity of the material and the effective size of the grains must be assumed, or at best, determined only at a few points, while the porous beds may extend for

miles and actually vary in both factors every few feet throughout their entire extent. The answer to the problem must therefore be found by estimating what probably would occur if the porous medium had a certain porosity and a certain definite character, and on this basis calculating limiting values which will afford a much better guide to the engineer than an assumption of flow based on the desire of the investigator to secure a certain quantity of water for a certain purpose.

It should be understood that any calculations of the velocity of flow of ground water can be regarded only as a rough approximation which will undoubtedly vary widely from the truth as developed by actual determination of flow by experiment or from the measurement of flow into wells, infiltration galleries, etc., and in consequence large factors of safety must be allowed in making estimates which are to serve as bases for investments.

From Equation 3 it will be seen that the flow of water through fine materials where capillary attraction is effective is found to vary directly with the slope; then the flow for a slope of 10% is one-tenth of the amount of flow under unity slope (see Table 48), while for slopes of 1% it is .01, for .1% it is .001, and for a slope of a foot per mile or $\frac{1}{5280}$ it is .00189 of the flow for unity slope. This does not apply to coarse gravels when the velocity of flow varies more nearly with $\sqrt{h}$.

Slichter has found that the flow of water will increase rapidly with the temperature, and that the flow at various temperatures compared with the flow at the temperature of 50° F., taken at unity, will vary as shown in Table 46. He also finds that the flow of water rapidly increases with the porosity, and that the flow for various porosities compared with the flow for a porosity of 32% taken as unity will vary as shown in Table 47.

TABLE 46.

Effect of Temperature on Flow of Water Compared with Flow at 50° F. = 1.00

Temperature Fahrenheit	32°	35°	40°	50°	55°	60°	65°	70°	75°	80°	90°
Relative Flow	.74	.78	.85	1.00	1.08	1.16	1.25	1.34	1.42	1.51	1.70

TABLE 47.

Effect of Varying Percentages of Porosity on Flow of Water Compared with Porosity at 32% = 1.00

Porosity or Percent of Voids	30	32	34	36	38	40
Relative Flow	.81	1.00	1.22	1.47	1.76	2.09

Slichter has also determined that the flow of water through various classes of material will vary under conditions of 50° F. temperatures, 32% porosity and with unity gradient, approximately as given in Table 48.

TABLE 48.

Transmission coefficient (k) or Velocity of Flow of Water with Unity Slope at 50° F. and 32% Porosity in Various Soils.

(In feet per minute)[15]

		Sand				Fine
	Silt	Very Fine	Fine	Medium	Coarse	Gravel
From	.00012	.003	.011	.07	.28	1.1
To	.002	.009	.046	.26	1.02	28.0

The quantity of water flowing in a given section of material may be found by the expression

(4) $Q = vap$

in which

$Q =$ Cubic feet per minute
$v =$ Velocity determined as above
$a =$ Area of cross section $\times \dfrac{\text{porosity}}{100}$
$p =$ Porosity

For example, determine the quantity of water flowing through 1000 square feet of fine gravel (of maximum coarseness) with a temperature of 60° Fahr., a porosity of .40 and a gradient of 20 feet per mile. The flow at unity gradient in such material is 28 feet per minute, and a gradient of $\frac{20}{5280} = .00379$; hence the velocity of flow at this gradient will be .00379 times 28 = .106 feet per minute. For a temperature of 60° F. this will be increased by 16%, and for a porosity of .40 by 109%; hence the actual velocity will equal .106 times 1.16 times 2.09 = .257 feet per minute. The flow area *a p* will equal 1000 square feet times .40 = 400, and the quantity of flow will equal .257 times 400 = 103 cubic feet per minute or 1.7 cubic feet per second.

The opportunities for gross errors in such computations as are made above are obvious, and yet the extreme case which can reasonably be assumed will often correct false impressions of possible capacities which otherwise would lead to serious results. Where more detailed information is necessary, it may sometimes be secured by the actual measure-

[15] The transmission coefficient *k* is the flow that will take place in a column of the selected material of standard porosity (32 per cent) at standard temperature (50° Fahr.) and under unity slope, that is with a head (*h*) equal to the length of the column of material (*l*) which condition is found in a vertical column with the water surface standing at the surface of the material.

ments of ground water velocity as suggested by Slichter in 1902.[16] Prof. Slichter's method is to sink two or more wells into the underflow, separated in the direction of flow by a certain known distance. By introducing an electrolyte into the higher well and utilizing electrical means, the time of passage of the water containing the chemical can be ascertained by the deflection of an ammeter needle and the velocity of the underflow thus determined. It is to be noted that the velocity of the underflow in different parts of a section varies greatly in accordance with the materials, the porosities and the contour of the underground channel. (See Fig. 250.)

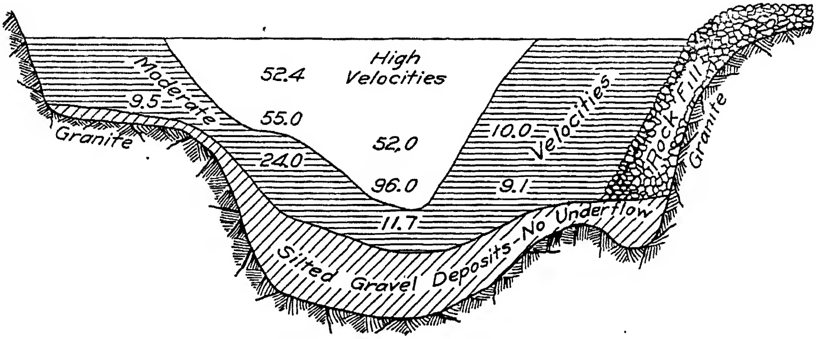

FIG. 250.—Velocity of Ground Water at Various Points in the Section of the Narrows of the Mohave River. After Slichter.

192. **Wells.**—Wells are excavations from the surface into underlying deposits and are usually constructed for the purpose of obtaining underground water for various purposes. In general, the waters have to be raised by some form of pump but occasionally with artesian conditions the water will flow at the surface. A well is therefore an artificial outlet for ground water, and when pumping is begun the first effect is to lower the hydraulic gradient or level of the ground water in the immediate vicinity of the well sufficiently to create the head necessary to produce the desired flow.

Wells in cracked, fissured and cavernous rocks (Fig. 251) depend on local conditions for their yield. These conditions can seldom be determined except by actual construction, although previous local experience may furnish a valuable guide as to what may be expected in new construction. Successful wells in crystalline and limestone rocks must reach water bearing cracks or fissures and a failure to encounter such

[16] Water Supply Paper No. 67, by C. S. Slichter, The Motion of Underground Water. Water Supply Paper No. 110, C. S. Slichter, Underflow Meter used in Measuring Movements of Underground Waters.

conditions will result in dry wells (Fig. 251, A & B). Wells in clay deposits containing sand beds or pockets are subject to similar contingencies (Fig. 251, C). Sometimes adjacent wells may furnish supplies of water which differ widely in mineral content or in organic purity on account of quite different sources from which their supplies are derived. (Fig. 251, D.)

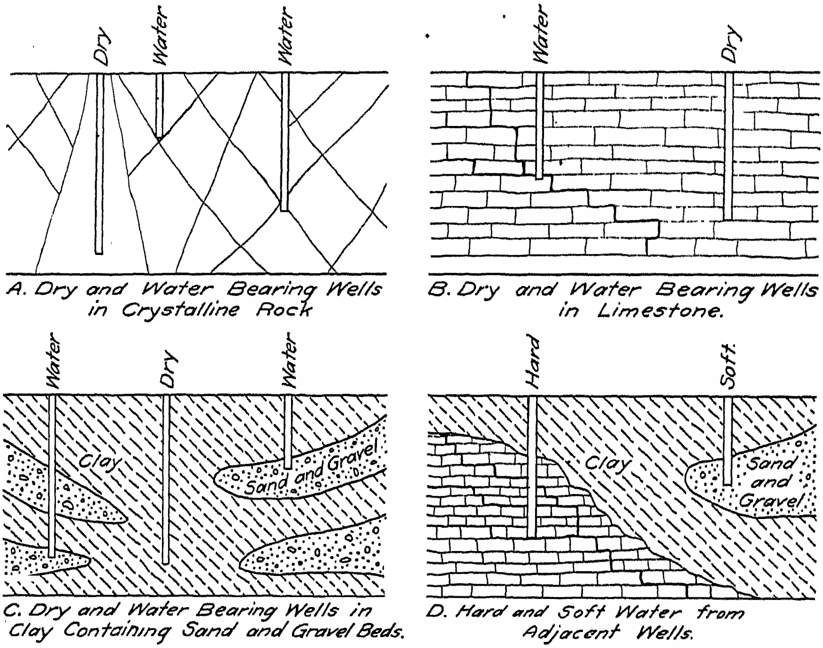

FIG. 251.—Conditions Favorable and Adverse to Securing Satisfactory Wells.

The quantity of water which may be secured from any well can in general be determined only by actual test. Such tests are usually made by pumping the well continuously for a considerable period; but even then the effects of long dry periods on the supply can only be estimated. For small supplies such tests are quite satisfactory but for large supplies the ultimate results are more or less problematic.

The principles of the flows of water in beds of sand and gravel of fairly uniform character are more readily determined. The principles of flows into wells are essentially the same as those for natural flow of ground water into streams or other natural outlets, and the continuous operation of the well tends to exhaust the ground water, to reduce its elevation in adjacent strata and gradually to increase the depth from which it has to be raised. As the water producing area created by the

construction of the well is comparatively small, the gradient necessary for the production of considerable supplies is correspondingly large.

Turneaure[17] has shown that when a well is sunk through any water bearing sand stratum the flow will be given by Equation 5.

$$Q = \frac{(y^2 - h^2)\pi kp}{\log_e \frac{x}{r}} \tag{5}$$

in which

Q = Quantity of water in cubic feet per day
r = The radius of the well in feet
k = Transmission constant of material
p = Porosity of the water bearing material
h = Height of water above the base of the water bearing stratum
y = Height of any point in the ground water plain above the bottom of the well at x distance from the well
x = Distance of any point in the ground water plain from the center of the well
$\log_e x$ = Hyperbolic logarithm of x

From this equation the slope of the cone of depression can be determined. (Fig. 252, A.)

When pumping first begins this area of depression will gradually widen and affect the ground water for some considerable distance in every direction, and its slope will be somewhat modified by the normal slope of the ground water and the direction of its flow. The continuous pumping of wells from superficial deposits will gradually reduce the ground water level at continually increasing distances from the well until, if the supply be sufficient, a new ground water gradient is established which will be maintained as long as the relations of supply and demand obtain. If the supply is practically inexhaustible, the cone of depression will finally assume a permanent form with a fixed circle of influence having a diameter x beyond which the ground water will not be lowered and the ordinate y will equal H. Under these conditions Equation 5 may be written[18]

$$Q = \frac{\pi kp\ (H + h)\ \ (H - h)}{\log_e \frac{x}{r}} \tag{6}$$

From which it is apparent that the supply will be proportional both to $H + h$ and to $H - h$, which has been found to be the case in many

[17] Public Water Supplies, F .E. Turneaure and H. L. Russell, 2d Ed., 1908, p. 279.

[18] Ibid, p. 213.

actual tests. From this equation it is understood that for small depressions in the ground water level the quantity of water will vary almost directly with the head but that for considerable depressions the increase in quantity is small. (Fig. 252, B.)

In deep wells where the reduction in head even if considerable is usually small with relation to the total depth of the wells, the flow is almost directly proportional to the reduction in head below the hydraulic gradient. (Fig. 253.)

When, however, the diameter of the well is small in proportion to the

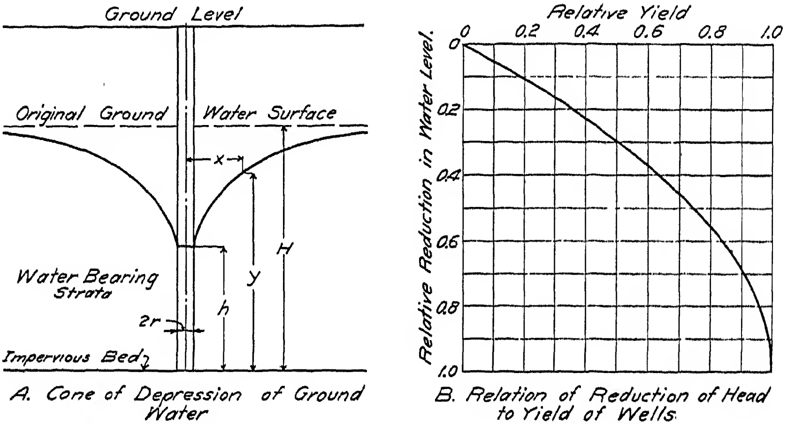

FIG. 252.—Principles of the Hydraulics of Wells.

flow, the friction in the casing will reduce the discharge and this effect must be taken into account in any estimate of the yield of wells.[10]

The elevation of ground water in wells is subject to all the seasonal variations of supply together with the additional factor of demand created by its use. The waters rise and fall with the rainfall and the season (Fig. 254), and the depth of the well and the pumping appliances used must be adjusted to meet all such conditions. As noted, every well in active operation creates in the surrounding water bearing strata a cone of draft dependent upon the principles discussed and affects the ground water gradient for a greater or less distance from the well, in accordance with the demand for water and the pervious character of the strata.

Where a single well is insufficient to supply the amount of water desired, and additional wells are constructed, they must for economical

[10] See Public Water Supplies, F. E. Turneaure, page 287.

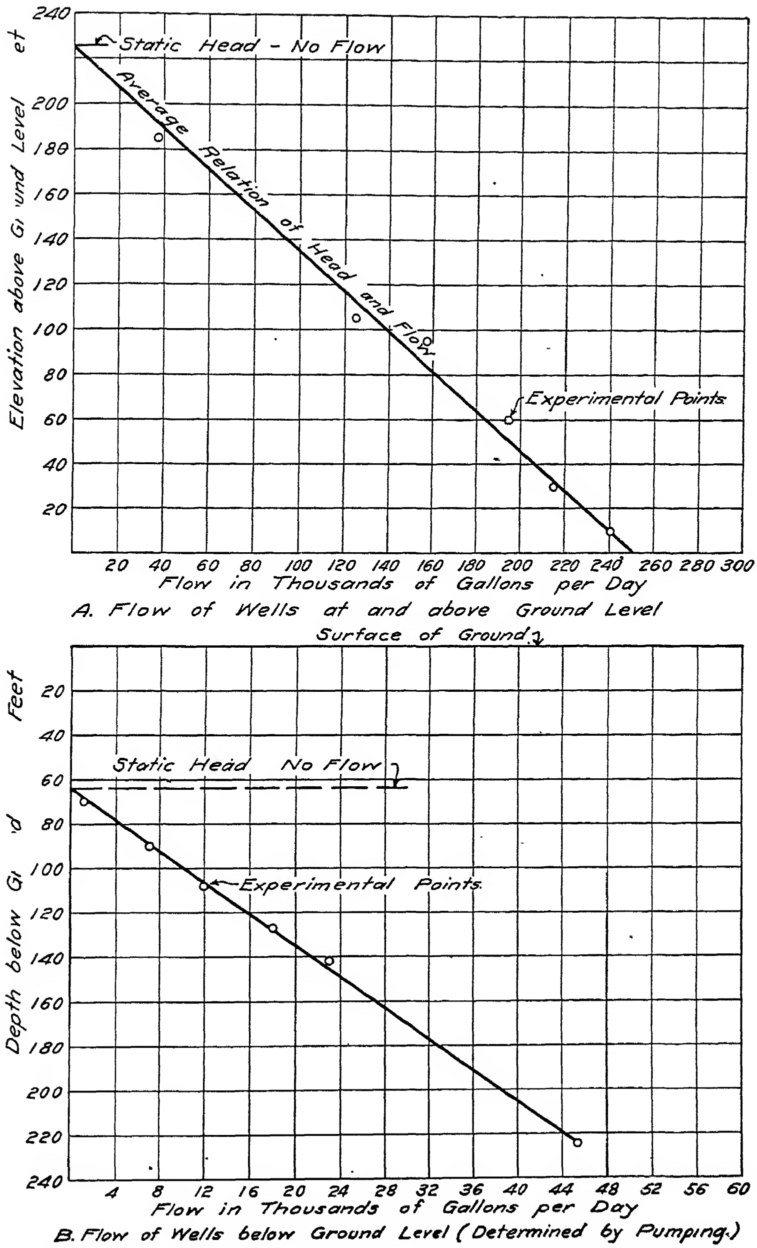

FIG. 253.—Flow Measurements from Certain Australian Wells.*

*Artesian System of Western Queensland, C. J. R. Williams, Proc. Inst. C. E., Vol. 159, p. 315, 1904–5.

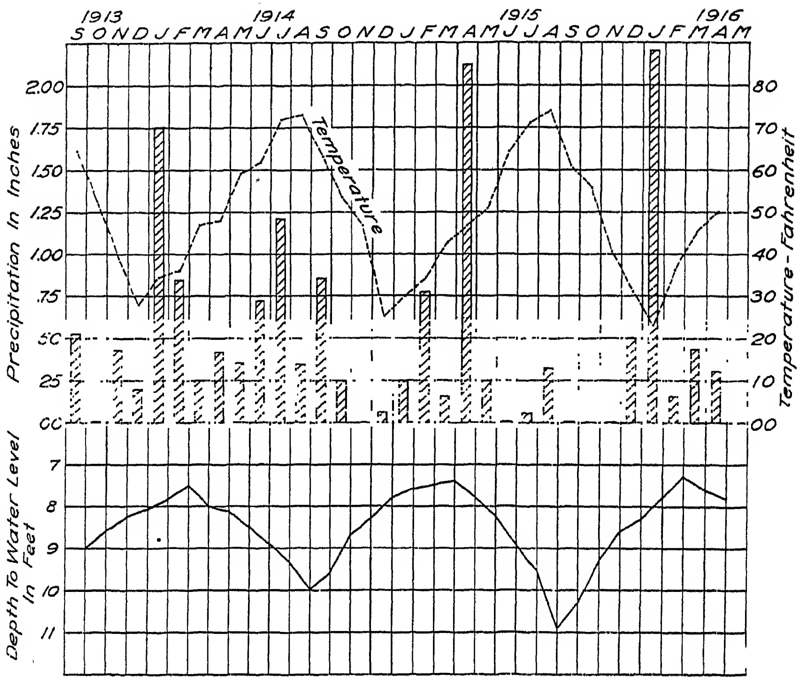

Fig. 254.—Variations in the Elevation of Water Surface in Wells due to Rainfall and Season. After Meinzer (see page 426).

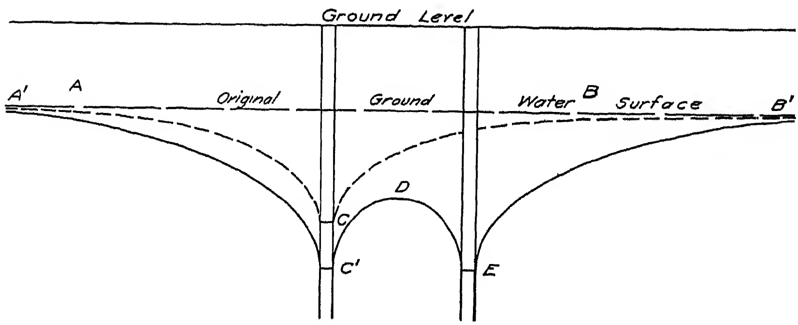

Fig. 255.—Illustration of the Interference of Wells.

reasons be constructed at sufficient distances from other wells so as not to interfere greatly with the cone of draft; otherwise the capacity of the wells so constructed will be reduced (Fig. 255). It is usually impracticable to construct wells in such manner that no interference will occur and various practical considerations must furnish a basis for their

proper adjustment. Where flowing wells are developed in the artesian areas they often furnish a convenient and economical method of obtaining water supplies, especially when the flow is sufficient to meet the demand. A successful well of this kind in a thickly populated community, however, soon brings about the construction of similar wells and as the wells increase in number and the quantity of water obtained increases in volume, the hydraulic gradient is gradually reduced until the supply required is so great that the wells cease to flow and pumping appliances have to be introduced in order to obtain the necessary supplies. As the demand for water supply increases the hydraulic gradient is farther and farther reduced until finally the water has to be raised from a considerable depth and the necessary expense involved finally limits the demand. The hydraulic gradient then becomes essentially permanent if the quantity of water in the strata and the drainage area of its outcrop are sufficient to maintain it.

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CHAPTER XVI

STREAM FLOW OR RUNOFF

193. **Source of Runoff.**—The water flowing in streams is derived from two sources, the amount of each being dependent upon the rainfall and on many other physical conditions on the drainage area:

1. That portion of the rainfall which passes directly into the streams as surface flow and which is the principal cause of sudden increase in flow and of floods.

2. That portion of the rainfall which sinks into the ground to reappear as springs and ground flow at more or less distant points, and which in general is the principal source of the ordinary dry weather flow of streams, although in some cases surface storage (i. e. lakes and swamps) becomes a still more important source of dry weather flow. A portion of this seepage may pass into the deep strata and flow away from the drainage area, reappearing in the lower valley or perhaps in distant areas, or even in the sea, but such losses from the seepage water are usually very small.

The runoff is that portion of the rainfall that is not absorbed by the deep strata, utilized by vegetation or lost by evaporation and which finds its way into streams as surface flow. The demands of seepage, vegetation and evaporation are usually first supplied and the runoff is therefore the overflow or excess not needed to supply these demands on the rainfall, or that portion which, on account of topographical conditions, has moved so rapidly that seepage and evaporation have not had time to affect it.

The portion of the flow of streams derived from the ground water is that portion of the seepage on the drainage area that has passed downward into cracks, fissures or porous beds of the higher parts of the drainage area, until it has encountered impervious material which has prevented its further descent and forced it to some outcrop that has been exposed by the development of the drainage channel into which it discharges.

194. **Importance of the Study of Runoff.**—The study of runoff is important to the engineer in connection with the investigation of public water supplies, water power, irrigation, drainage, storm water sewerage,

flood protection, navigation, river regulation, etc. In general, the interest of the engineer centers around three phases of this question:

1st. The total quantity of flow, its annual and seasonal variation and the possible methods of its equalization or concentration.

2d. The maximum quantity of flood flow, its variation during the period of flood, and its reduction or control.

3d. The minimum flow and its possible modification by storage or auxiliary supply.

Averages are of little moment. It is not satisfactory to show that the average water supply is sufficient if in one season or year there are flood conditions and in another there is a serious shortage of water or perhaps no water at all available. Water like food must be available when needed, and averages are almost valueless for most engineering purposes. A public water supply must command an adequate quantity essentially constant during the year and increasing with the growth of the community. A supply for irrigation must be adequate in quantity and available during each growing season. For successful water power development a continuous adequate supply must be existent or must be made available or else auxiliary power must be provided to take its place. For navigation a sufficient supply must be available during every navigation season.

In flood protection, drainage, storm water sewerage, and in the design of spillways, channels or reservoirs to pass or control the high waters of flood periods, the question of the maximum flow and the rate of increase and subsidence of floods are matters of the greatest importance.

In some engineering problems the whole range of variation is of importance, while in others the maximum or minimum may be the important factor.

195. **Occurrence of Runoff.**—In general upland areas are wet only during and for a short time following rainstorms until the moisture sinks into the soil or rock, is taken up by vegetation or is evaporated, or until the surface water drains into the lower lands.

The lower lands remain wet for a longer period as they receive not only the direct rainfall but also the surface runoff and perhaps the seepage from the saturated soils of the higher lands. When drainage is poor the low lands may hold the water for considerable periods and in the case of swamps and marshes may be permanently overflowed except possibly in very dry seasons, while in other cases, permanent pools, swamps and lakes that are never known to become dry result from imperfect drainage.

The channels of streams undergo similar variations. Even in humid regions with small drainage areas and high gradients drainage channels may rapidly pass the waters from a rainstorm and in a few days or even hours become as dry as the surrounding country. In such cases these drainage channels are called dry runs. In streams draining larger areas in humid countries, the varying rainfalls and consequent runoff from widely separated areas, the seepage from porous soils and the drainage

FIG. 256.—The Colorado River at Austin, Texas, in Flood.

of lakes and swamps furnish a constant supply, variable in magnitude but perhaps seldom or never failing and stream flow becomes perennial.

In arid and semi-arid countries the variation in flow is more marked and the drainage channels from greater areas become dry at times. The Colorado River at Austin, Texas, drains an area of about 37,000 square miles and the runoff has been known to vary in quantity from 250,000 cubic feet per second to 9 cubic feet per second. This wide range in flow of the Colorado River is well illustrated by Fig. 256 which shows the river passing over the dam during flood stage, and Fig. 257, which shows the extreme low water flow passing through a narrow channel and through a single gate in the dam.

The wide variation in the flow of streams is also shown by Figs. 258 to 261, pages 436 to 439 inclusive. In each case the variation in the flows of the twenty streams used as examples is illustrated by an annual

hydrograph for a year of high flow and a year of low flow, so that approximately maximum and minimum conditions are indicated. These rivers are so chosen as fairly to represent the great variations in flow in different parts of the United States; and the location of each stream is shown by the map, Fig. 262, page 440. These hydrographs show that the variations from day to day are great and that while in general the

FIG. 257.—Extreme Low Water Flow of the Colorado River at Austin, Texas.*

high water and low water seasons in any stream are essentially similar, they nevertheless are subject to considerable variation. It is quite evident from these hydrographs that the subject of runoff is by no means a simple one and that for practical engineering purposes even approximately correct conclusions call for a careful consideration of the many factors on which depend the great variations in flow of different streams and even of the same stream.

196. Difficulties of the Problem.—Practical problems in stream conservancy involving questions of water supply are greatly complicated by the numerous factors which modify or control this phenomenon and which are so intimately related and intermixed in their effects that the

*Photo by Mr. Guy Collett, Austin, Texas.

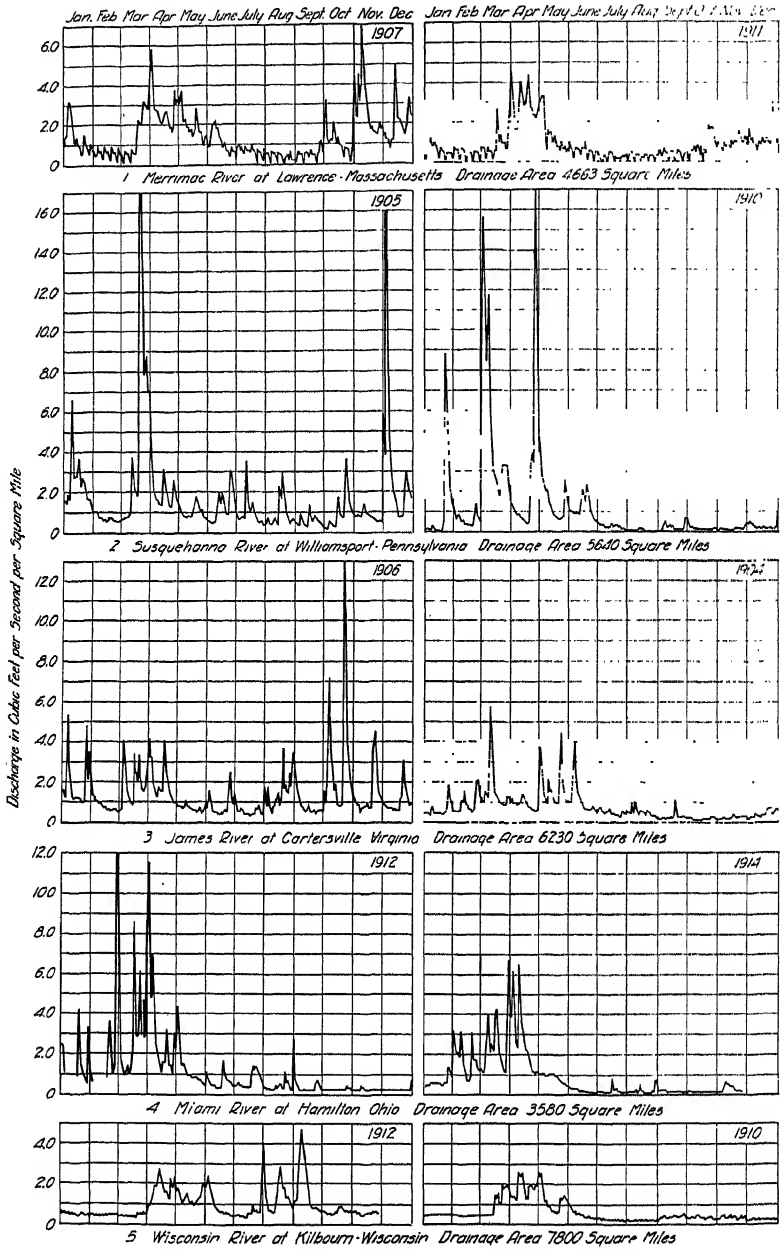

FIG. 258.—Hydrographs of Various Streams for Years of High and Low Flow.

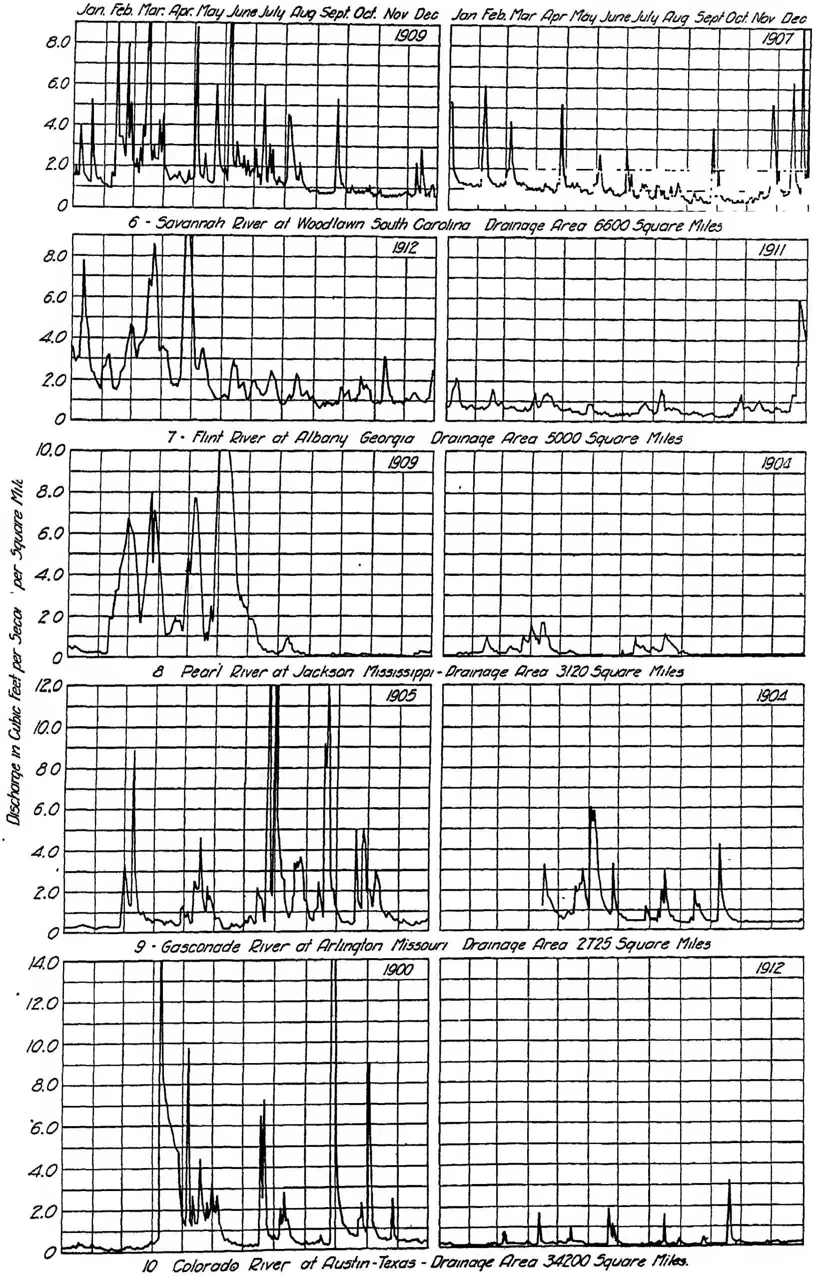

FIG. 259.—Hydrographs of Various Streams for Years of High and Low Flow.

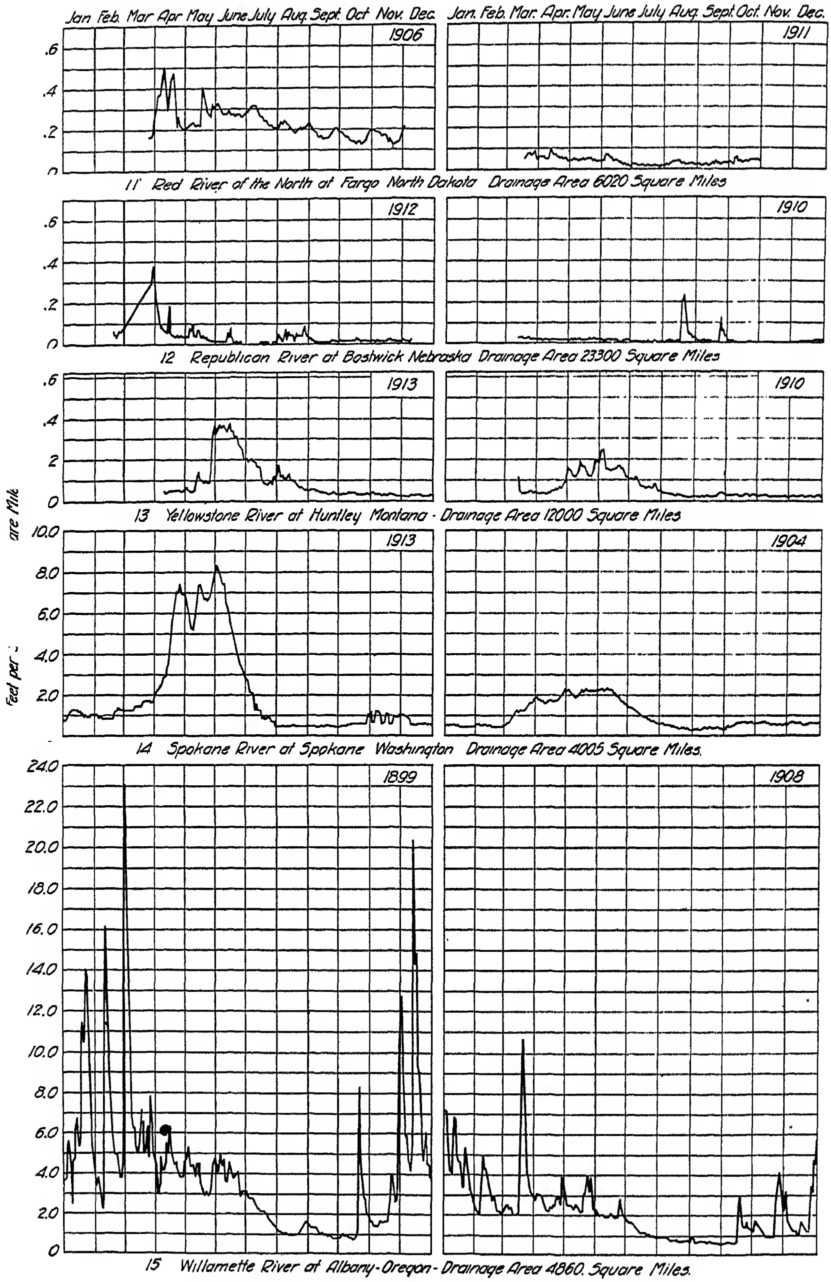

FIG. 260.—Hydrographs of Various Streams for Years of High and Low Flow.

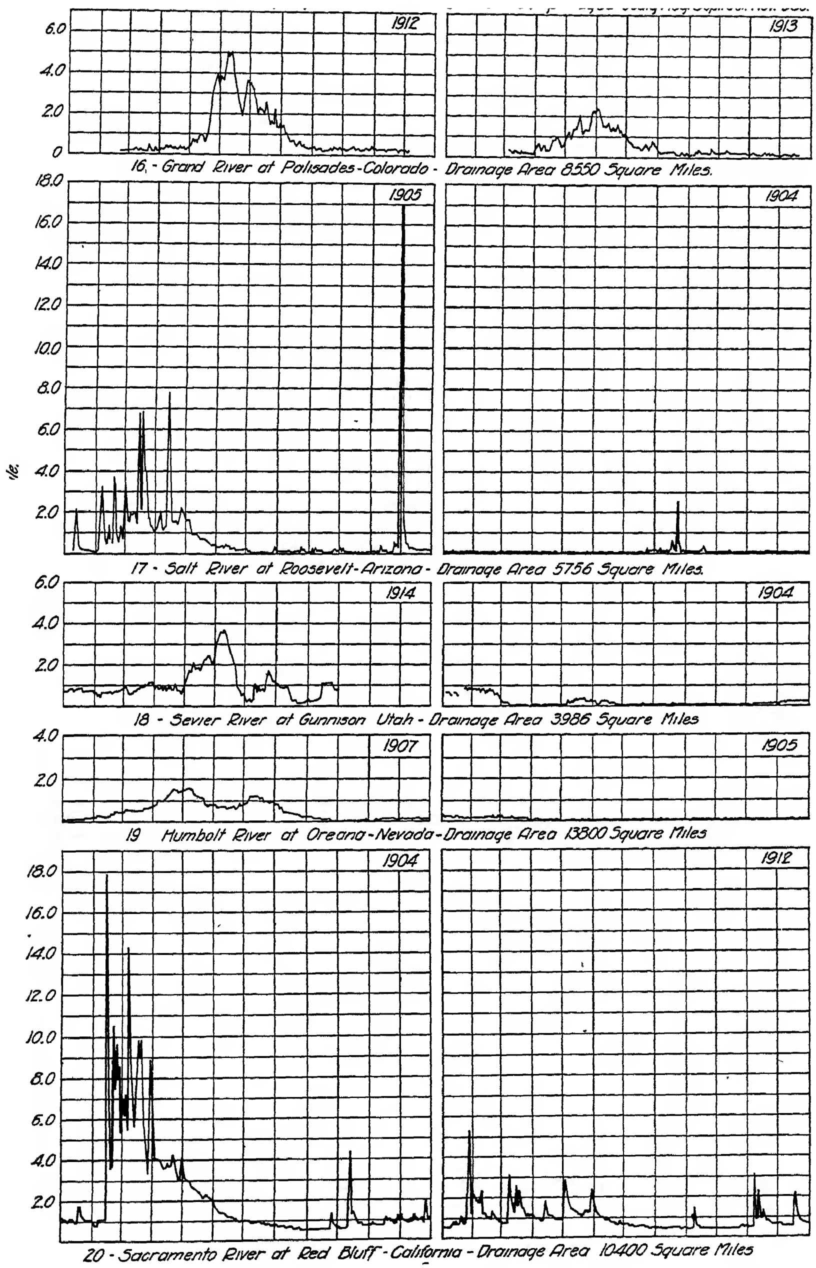

FIG. 261.—Hydrographs of Various Streams for Years of High and Low Flow.

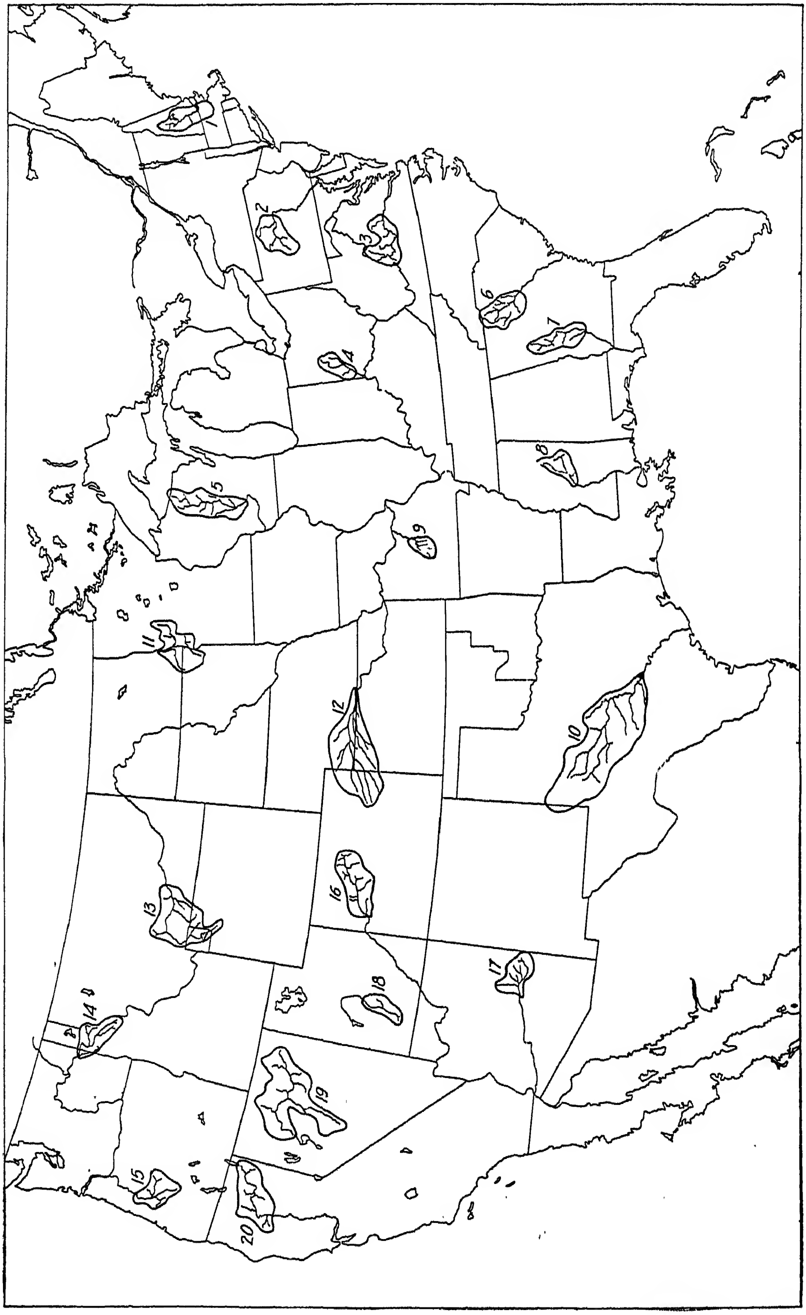

FIG. 262.—Locations of Drainage Areas of Streams whose Hydrographs are shown in Figs. 258 to 261.

relative influence of individual factors, if independently considered, becomes difficult to differentiate and practically impossible to evaluate. The effects of individual factors considered under such a multiplicity of varying influences are therefore frequently misunderstood and often misinterpreted. If, however, the factors of fundamental problems are first considered in their most simplified relation and their effects under such conditions determined, the modifying effects of additional complicating factors can then be more readily understood and appreciated.

For engineering purposes, the conditions of uniformity of flow and sufficiency of water supply are the most favorable and the conditions of maximum variation in flow and deficient water supply are the most unfavorable. From personal observation of the flows of numerous streams in which certain factors largely predominate, it is not difficult to differentiate the effects and segregate those conditions which will, if prevailing, result in either the most favorable or the least favorable water supply of the consequent streams. Such conditions are outlined in Cases I, II and III, in Sections 205 to 208.

197. **The Factors of Runoff.**—The factors which control or modify the runoff of streams are so inter-related that when any enumeration of such factors is made the question may logically be raised as to whether some of those listed are not similar to or a part of others, and almost any such enumeration might be classified and discussed in other ways with equal reason.

For the purpose of this discussion these factors are listed as follows:

1. Precipitation.
2. Geographical relations of the drainage area.
3. Topography and Geology.
4. Meteorological conditions.
5. Surface conditions.
6. Storage conditions.
7. Artificial use and control.

A detailed consideration of these factors of stream flow, both individually and in their inter-relations, is necessary for the intelligent study and understanding of stream flow. Such a consideration within the limits of a single volume is impossible. The principal factors and their brief consideration are summarized in the following sections.

198. **Precipitation.**—Precipitation is of primary importance for without precipitation there can be no stream flow. Precipitation modifies runoff in accordance with the quantity and manner of its occurrence.

The important factors of precipitation to be kept in mind in the study of runoff are as follows:

A. Causes of Precipitation. (See Sec. 82, p. 159.)
  a. Local conditions which may give rise to precipitation. (See Sec. 84, p. 165 et seq.)
  b. Movements of storms which produce precipitation. (See Sec. 40, p. 66.)

B. Factors of Local Precipitation. (See Secs. 84 to 88, p. 165.)
  a. Location relative to sources of vapor from which precipitation is derived. (See Sec. 85, p. 166.)
  b. Location relative to storm tracks. (See Sec. 92, p. 176.)
  c. Local topography. (See Sec. 84, p. 165, also Chap. XII, p, 283 et seq.)

C. Quantity and Distribution. (Chaps. IX and XI.)
  a. Total annual amount of precipitation and its variations. (Chap. IX, p. 200.)
  b. Distribution of precipitation throughout the year, and variations. (Chap. X, p. 228.)
  c. Intensity of individual storms. (See Sec. 119, p. 243, et seq.)
  d. Geographical extent of storms. (See Sec. 129, p. 266, et seq.)

D. The Amount which occurs as Snow:

  The quantity that falls as snow or which freezes as it falls is retained (less evaporation) on the drainage area until higher temperatures cause it to melt and to flow to the stream, perhaps some weeks or months later.

In general, the following conclusions are warranted.

Other things being equal, runoff will increase:

With the total amount of rainfall (with exceptions).
As the intensity of the rainfall increases.
As the extent of the storm on the drainage area increases.
As and when evaporation decreases (in fall, winter and spring).
When vegetation is inactive (in fall, winter and spring).
With precipitation stored as snow and ice (in spring).
With precipitation stored underground (dry weather flow).

Precipitation will have comparatively little effect on runoff:

When it occurs in very light showers.
When evaporation and vegetation are active (in summer).
When the storm covers only a small portion of the drainage area.

Fig. 263 shows the relations of the total annual rainfall to the total annual runoff on four American streams, viz., the Sudbury, the Ohio, the Merrimac and the Coosa.

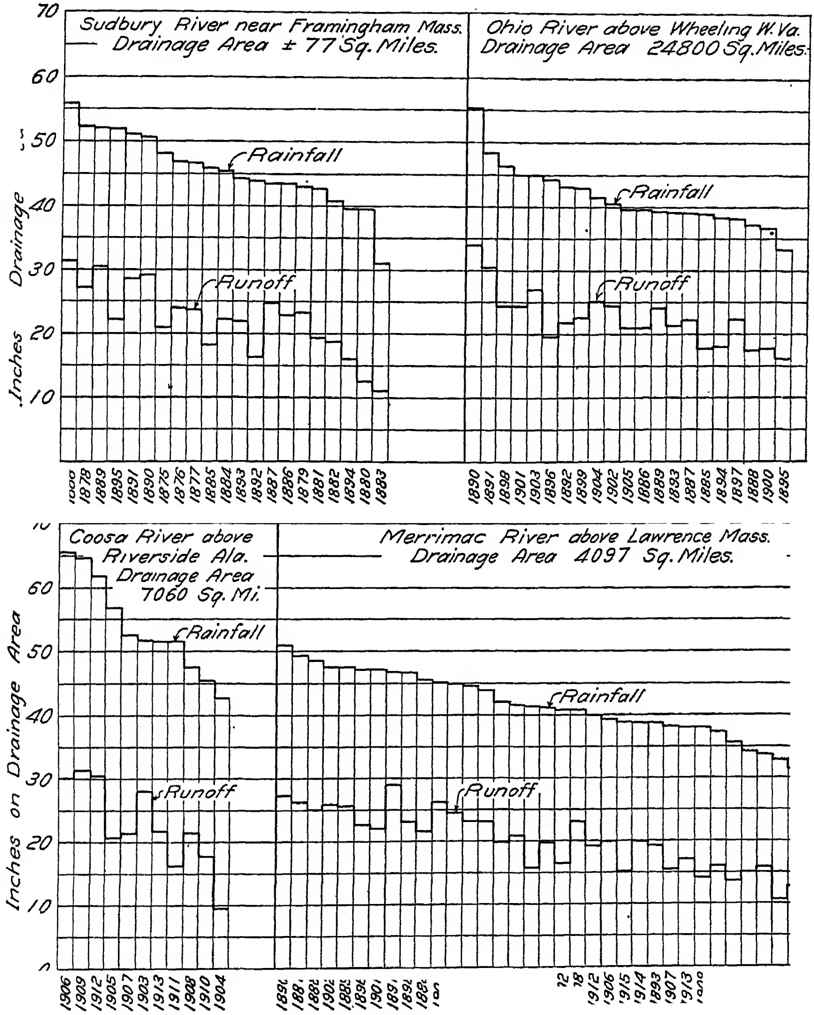

FIG. 263.—Relation of Total Annual Rainfall to Total Annual Runoff on Certain Streams in the United States.

It will be noted that while in general the runoff increases with the increase in rainfall there are exceptions to the rule and that evidently no constant relations exist.

199. Geographical Relation of Drainage Area.—The important factors in these relations are (a) size, (b) shape, and (c) location of the drainage area. Each of these factors may have a marked effect on the quantity and regularity of the flow of a stream.

(a) Most storms are more or less limited in extent but often include centers of high concentration. A limited storm might cover a relatively small drainage area with marked effect on the runoff, but would have a much different comparative effect on the flow from a large area.

A small area which becomes the center of intense precipitation will furnish relatively great flood discharges and consequent great variations in flow. As the size of the drainage area increases, the possibilities of intense precipitation over the entire drainage area are greatly reduced, and with this increase floods in the main streams become correspondingly less in relative magnitude.

(b) The fan arrangement of tributaries results in high flows reaching the main stream at the common center of discharge of the tributaries at about the same time, and causes congestion and consequent extreme flood conditions (Fig. 108, page 197), while a fern leaf arrangement of tributaries (Fig. 264) will in general result in less extreme floods.

(c) The geographical location of the drainage area may have a similar effect. Should the drainage area lie in a direction parallel with the path of intense storms, the precipitation and flow may be greatly increased over those which occur where the area extends across these storm paths, and consequently commonly receive intense rainfall only over a portion of the area.

The hydrographs of small areas often show the effects of heavy rains by an immediate and marked increase in the flow, as will be noted by a comparison of the hydrographs of Perkiomen Creek and the Kennebec River (Fig. 265, page 446). On drainage areas of small streams where pervious deposits largely obtain, the rainfall is rapidly absorbed and does not radically affect the runoff nor do these streams show greater fluctuations than larger streams: for example, compare hydrographs of the Coosa River and Nottingham Creek (Fig. 265). Large streams do not feel the immediate effect of rainfall on account of the time required for the runoff to reach the main stream.

The flow of large streams is also modified by the fact that uniform conditions of rainfall seldom obtain on the entire area. On large drainage areas conditions of rainfall may prevail on one or more of the tributaries only, while on other portions of the drainage area no rain may be falling, with the result that the larger the stream the less become the extremes and the greater the uniformity of flow. In some

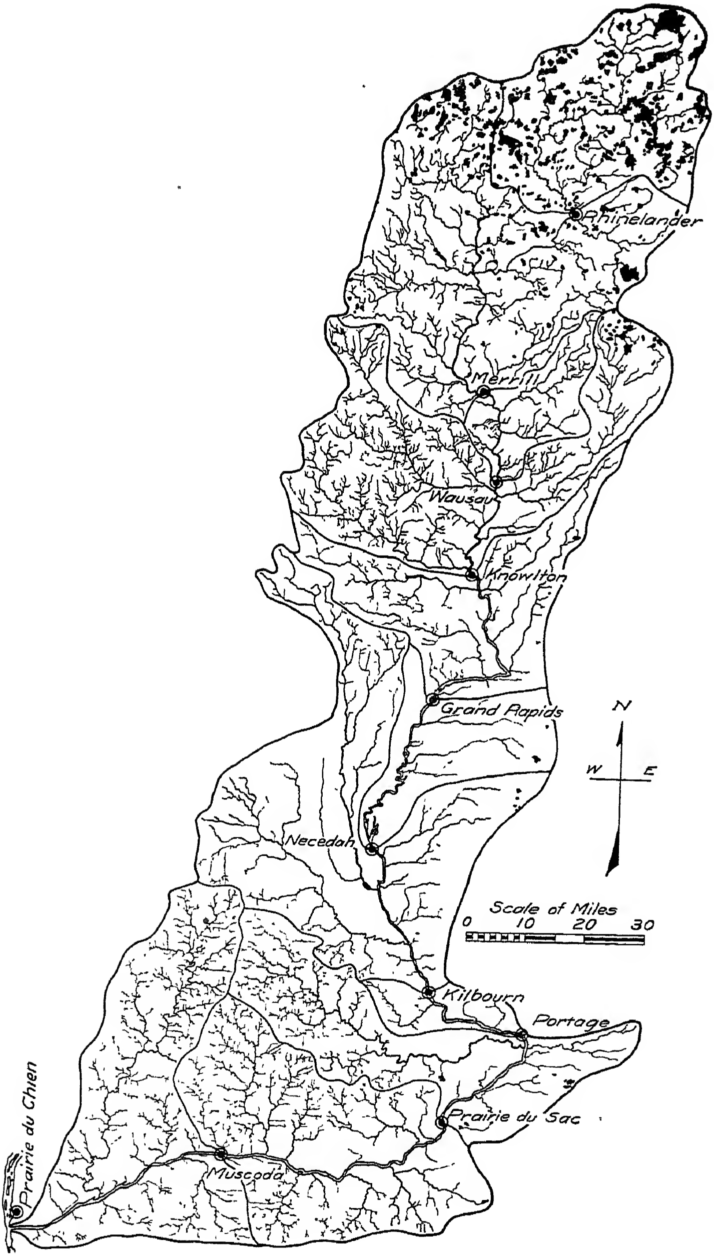

FIG. 264.—Drainage Area of the Wisconsin River.

cases streams which are fed by mountain snows at particular seasons as for example, the Sacramento River (see Fig. 261, Hydrograph 20, page 439) or in some locations subject to occasional general heavy rain-

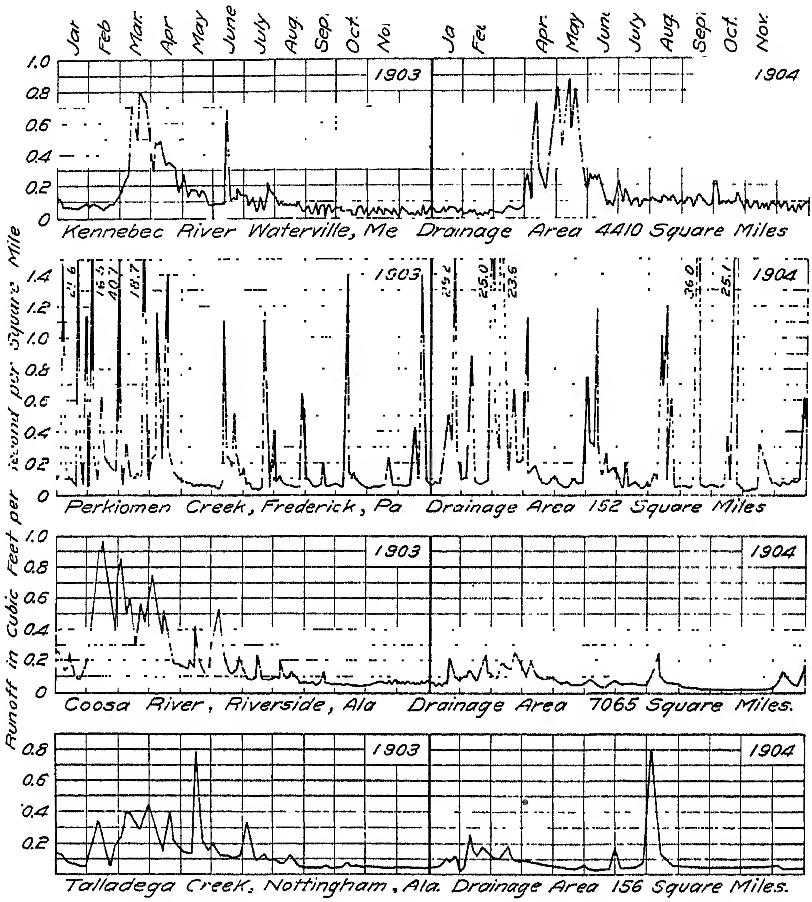

FIG. 265.—Hydrographs of Certain Rivers of the United States (see page 444).

falls, as in the case of the Colorado River (see Fig. 259, Hydrograph 10, page 437), even large rivers may be subject to violent changes in runoff and to excessive flood conditions.

200. Topography and Geology of Drainage Area and Channel.

A. Topography of the Drainage Area—The important features are:

(a) As to whether the surface is level or inclined, and the degree of inclination.

(b) As to character of area, whether smooth or rugged.

B. Geology of Drainage Area:

(a) Soils and rocks, their nature and whether pervious or impervious.

(b) If pervious, whether such pervious deposits are (a) shallow or deep; (b) level or inclined; whether the outlet or point of discharge of the pervious deposits is (c) in the lower valley of the same river, or (d) in valleys of other rivers, or in the sea.

C. Underflow Conditions.—As to the condition of the channel of the stream:

(a) Whether pervious or impervious.

(b) Whether the bed contains more or less extensive deposits of sand and gravel, permitting of the development of a more or less extensive underflow.

(c) If impervious, whether the strata are cracked and fissured.

A. Topography.—Mountainous topography favors orographic precipitation for considerable distances from and on the windward side of the mountains or on the side toward which barometric changes of the atmosphere advance. On the other hand these same conditions give rise to a consequent diminution in precipitation on the leeward side of mountains.

The topography of a drainage area has a marked effect on the quantity and intensity of runoff. Abrupt topography is essential to quick runoff, while a flat slope, even with the drainage area under similar geological and surface conditions, is productive of slow surface flows and favorable to both seepage and evaporation.

If the water stands on the surface of a comparatively level and pervious deposit, or flows slowly across it, considerable opportunity is given for seepage into the soil and rocks of the drainage area; whereas, if the surface is steeply inclined, a rapid flow of water over the same surface will materially reduce the quantity of seepage.

With impervious deposits, gradient may only slightly modify the quantity of water entering the strata which, in any event, may be insignificant.

B. Geological Conditions.—Geological conditions are frequently of great importance in their influence on the quantity and regularity of runoff. If the geological deposits of the drainage area are highly impervious, the surface flow will receive and transmit the water into the mass only through the cracks and fissures in the rock. Pervious ma-

terials, such as sandstones, sands, gravels and cracked or fissured rocks, induce seepage, retard runoff, and, if such deposits are underlaid with an impervious bed, provide underground storage which impounds water away from the conditions which permit evaporation, and hence tends to increase runoff and equalize flow. On the other hand, if such pervious deposits possess other outlets outside of the stream channel and drainage area, they may result in the withdrawal of more or less of the seepage waters entirely from the ultimate flow of the stream. Coarse sands and gravels will rapidly imbibe the rainfall into their structure. Fine and loose beds of sand also rapidly receive and transmit the rainfall unless the precipitation is exceedingly heavy under which conditions some of it may flow away on the surface.

Many of the highly pervious indurated formations receive water slowly and require a considerable time of contact in order to receive and remove the maximum amount.

In flat, pervious areas, rainfalls of a certain intensity are frequently essential to the production of any resulting stream flow. In a certain Colorado drainage area, the drainage channel is normally dry except after a rainfall of one-half inch or more. A less rainfall, except under the condition of a previously saturated area, evaporates and sinks through the soil and into the deep lying pervious sand rock under the surface which transmits it beyond the drainage area. Such results are frequently greatly obscurred by the interference of other factors, such as temperature, vegetation, etc.

The determination of the detailed geological conditions which may modify the resulting runoff from any drainage area, and the evaluation of the effect of such conditions on runoff, are practically impossible and can not be made with sufficient accuracy to furnish a safe basis for an estimate of the approximate results which will obtain therefrom without observations of the actual stream flow. The effects of such conditions, however, are important and sometimes furnish an explanation of quantitative differences in flow not otherwise explainable and often afford a warning of probable comparative differences in flows which must be expected from the variation in the conditions that obtain.

The difference in unit runoff of the Wisconsin River above Merrill and Necedah, Wisconsin (see Fig. 266, page 449), is probably due to the effects of the granite rocks above Merrill which produce a maximum runoff, while the pervious Potsdam deposits over the lower part of the drainage area and under the bed of the lower stream probably induce a considerable loss by seepage into that stratum and away from the channel.

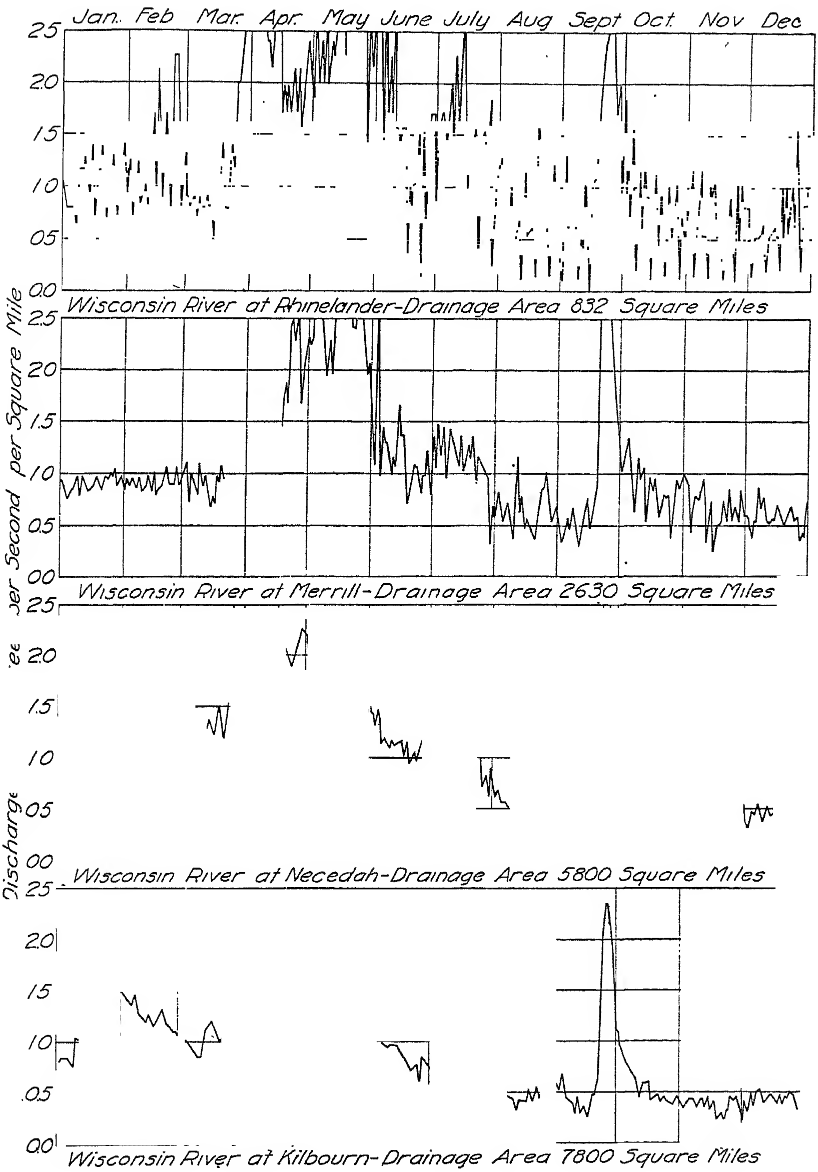

FIG. 266.—Hydrographs of the Wisconsin River at Various Stations.

C. Ground Water and Underflow.—Ground water proper flows underneath and at greater or less distance below the surface. Small streams sometimes occur in caverns and fissures in the rocks, particularly in the limestone regions.

The ground water proper usually has outlets in the lower portions of the drainage area upon which it falls as rain, and appears as springs along the banks and in the bed of the stream channel itself and is usually the main source of supply for the dry weather flow. Deep seated ground waters which enter the pervious formations may follow such formations to distant outlets perhaps on other drainage areas or into the sea.

Many streams occupy trenches, and occasionally broad valleys of considerable cross section, which are partially or largely filled with deposits of sand, gravel, silt, clays, etc. In such cases the pervious strata below water level are saturated and may transmit a considerable underflow. The Rock river from Lake Koshkonong, Wisconsin, to Rockford, Illinois (see Fig. 220, page 374), flows over a preglacial drainage valley 100 feet or more below the present river. This channel carries a considerable underflow from which many private water supplies are obtained. This is also the case in many Western river channels which carry surface water only during storms, but water can often be obtained from wells in the dry bed. In the dry season the surface stream in such channels may disappear entirely and the underflow still continue, as in the case of the Arkansas River at Wichita, Kansas, Fig. 244, p. 409. Such flows may be of considerable importance in sustaining water supplies from wells constructed in such deposits for public and private purposes and for irrigation as in the case of the Gila River underflow in Arizona, Fig. 242, page 407. While considerable quantities of water are obtainable from such sources, the possibilities of such sources are frequently overestimated where cross sections and ground water slopes are comparatively small. In some cases the rivers have been forced out of their ancient beds which have been filled but still afford passages for more or less underflow which may then be diverted entirely away from the stream. (See Fig. 223, page 380.)

201. **Meteorological Conditions.**—The important factors are:

A. Temperature.

(a) The annual and seasonal temperatures on the area, their duration and variation, and the resulting accumulation of snow and ice.

(b) The relation of extreme low temperatures to the occurrence of precipitation, and the possibility of the freezing of

ground surface at times of heavy spring rains, resulting in excessive runoff.

B. Barometric and Atmospheric Movements.
   (a) Relations to paths of storm centers.
   (b) Effects of passage of barometric centers of pressure.
   (c) Winds resulting from barometric conditions.

C. Evaporation.

A. Temperature.—Temperature often has a marked effect upon runoff. Snow falling on a drainage area, ice formed from the rain on the area, and ice over the surface of water are temporarily stored and will be released only when the temperature rises. In high latitudes and high altitudes low temperatures are productive of storage in the form of ice or snow, and the advance of the spring season with its consequent increase in temperature is often productive of floods from such storage without accompanying adequate precipitation. (See Fig. 267, page 452.) The saturated and frozen condition of the ground also frequently results in excessive floods from a comparatively small amount of precipitation where under other conditions the pervious drainage area would normally retain such rainfall without flood effects.

The sudden freezing of streams may cause an abnormal but temporary decrease in flow even where the sources are not seriously affected. The friction of flow of a river under ice is considerably greater than with open water, hence when ice is suddenly formed on a stream, not only is a considerable quantity of water congealed and temporarily withdrawn from the runoff, but the river must rise and fill a greater cross section in order to overcome the extra friction caused by the ice formation. Sudden temporary reductions of 50 to 75% in the flow of streams are sometimes occasioned in this way, which is usually partially recovered within a few days after the advent of the cold wave.

The occurrence, in high latitudes during periods of low temperature, of torrential rains such as occur in summer seems to be physically impossible on account of the small amount of moisture carried in the atmosphere during winter periods. (Compare Figs. 66 and 67, page 120.)

High temperatures, especially where accompanied by wind movements, also favor evaporation.

B. Barometric and Atmospheric Movements. Winds: (a) It has been pointed out that the paths of cyclonic storms are favorable to precipitation (see Sec. 92) and that the relation of such paths to the position and size of a drainage area under consideration may have an im-

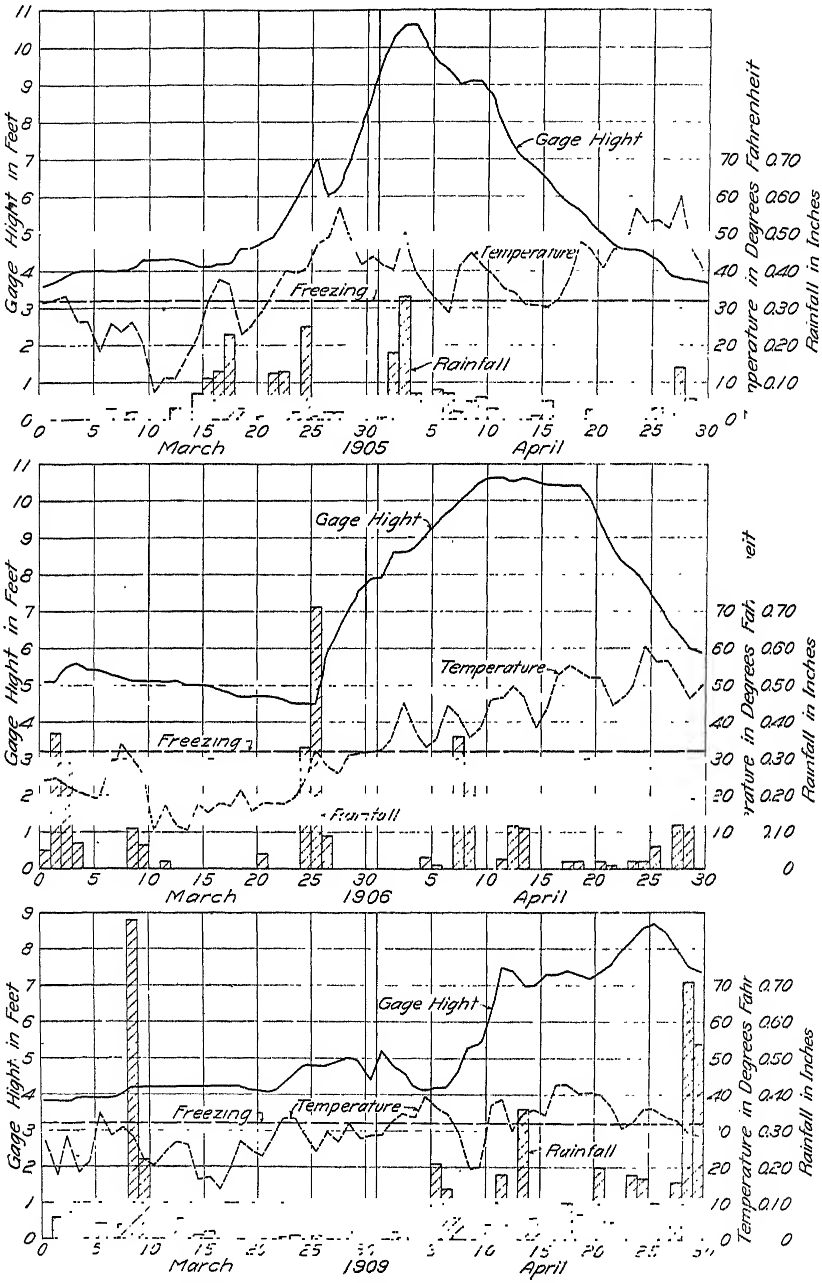

FIG. 267.—The Relations between Stream Flow and Rising Temperatures.

portant influence on the torrential character of the flow of the stream. (See Sec. 199.)

(b) Large rivers fed by great lakes are sometimes subject to sudden changes in discharge on account of barometric movements increasing or decreasing the elevation of water at their heads during their passage. (See Sec. 54.) Such a change is shown by Fig. 55, page 102, reproduced from the graphical record of the U. S. Lake Survey gage, located at the St. Clair River.

(c) The intensity and direction of the normal winds resulting from barometric movements or from local or seasonal conditions may have a considerably modifying effect upon the quantity of evaporation and, though sometimes insignificant, have a decided effect in increasing the amount of evaporation from exposed water surfaces, as the saturated air in contact with such surfaces is rapidly removed and fresh unsaturated air is brought into contact with them. Where these water surfaces are small and lie among the hills or are surrounded by forests, the effect of the wind on the same is greatly reduced and evaporation is less. Heavy and continuous winds by their effects on lake levels have a marked effect upon the flow of the streams which drain the lakes. (See Sec. 53, page 98.)

C. Evaporation. (See Secs. 67 to 79.) A large evaporation takes place from swamp and lake surfaces. In some localities this evaporation is fully equal to and in some cases even greater than the amount of rain that actually falls on the exposed water surfaces. If such areas occupied approximately the full drainage area, no runoff whatever would take place. While evaporation is a large item on exposed surfaces, the actual percentage of water surface on any drainage area is usually comparatively small, and the evaporation is therefore not so large a factor when the entire drainage area is considered. Swamps and lakes, therefore, tend to conserve and control the flood waters and undoubtedly in most cases add materially to the regularity of stream flow, although they frequently reduce its total annual amount.

202. Surface Conditions.—The drainage area may be all or in part:

A. Drained or undrained.

B. Natural or cultivated.

C. Bare or covered with vegetation, crops, grass lands or forests.

Surface conditions have a marked effect on runoff, but such effects are not always obvious.

A. Drainage.—The effects of lakes and swamps are discussed in Section 203, but the effects of the withdrawal of swamp area on stream flow

are not fully understood. In general, drainage work practically affects surface storage only although occasionally ground storage may be slightly affected. Open drainage canals and ditches bring the surface flow more directly and quickly into the stream and thus undoubtedly tend to increase the flood height. Cultivation and subdrainage, however, have an opposite effect as they improve seepage and ground storage conditions.

B. Natural and Cultivated Areas.—Cultivation of the ground produces two effects which influence runoff from a drainage area. The breaking up of the smooth surface of a field, especially in a semi-impervious deposit, undoubtedly will greatly facilitate the seepage of water into such deposits and will also decrease evaporation from the ground water (see Sec. 74, page 138). Cultivation, therefore, is frequently favorable to stream regulation. On the other hand, the cultivation of large areas that have previously existed in a natural condition has in some cases reduced to a considerable extent the water reaching the streams during the growing period. A compact sod on a considerable slope with large rainfall sometimes permits much greater runoff than is possible when the same area is broken and cultivated.

While seepage and evaporation are greatly modified by geological conditions as noted in Section 200, the conditions of drainage and surface covering may be of equal importance.

C. Forests and Vegetation.—A bare smooth surface is favorable to runoff and therefore to flood conditions. The presence of vegetation on a drainage area may materially decrease the rapidity with which water flows therefrom and such vegatation may or may not be favorable to the uniformity of the flow of a stream. A surface covered with vegetation may, to a considerable extent, delay the removal of rain during the smaller storm. The humus, due to forest growth, may form to some extent a minor storage which will prevent the immediate removal of the water of limited storms. When, however, the rain is extensive, the humus or covering of vegetation becomes saturated and the water then runs from the surface almost as freely as though no vegetation existed. The effect, therefore, of vegetation on runoff is to retard the earlier flows from the surface which, however, may be delivered to the streams at a later period. Such conditions may be favorable or unfavorable to higher flood conditions according to the intensity of the storm and the discharging time and capacity of other tributary streams of the same drainage area.

Of the amount of water actually held or retarded by vegetation, it is

obvious that the larger portion may be taken up by the vegetation and used in vegetable growth and expired by the leaves. The retention of the water in this way will increase evaporation. While in a minor way this vegetation may be considered as regulating stream flow, it prevents a certain amount of precipitation which might otherwise flow away, from ever reaching the stream. On an area of a pervious nature and with considerable gradient, the vegetation holding the water on the slope may assure a considerable extra amount of seepage which, with suitable geological conditions, may be returned to the stream through the ground water and thus assist in the regulation of the stream. Where, on the other hand, the deposits lie in a comparatively low gradient and are highly previous, the presence of vegetation on the surface will limit the flow of water into the underlying deposits and prevent the rapid seepage which would otherwise occur. Under such conditions the presence of vegetation on the drainage area will assure a loss to the stream flow caused by the increase in evaporation and vegetable use.

According to certain French measurements,[1] from 10 to 40 per cent of the rain falling on a forest never reaches the ground but is caught by the trees and re-evaporated. On the other hand, evaporation is greatly reduced within the forest shade and the loss either from wet ground or water surfaces thus protected is much less than in the open field. The melting of snow is retarded by the shade of the forest and the same is true of ice in thickly forested swamps, but the delay in the melting of snow or ice is not sufficient to reserve the supply until needed in the extreme low water periods of August and September.

Outside of the direct influence of forests on the immediate disposal of the rainfall, it must be noted that the roots from vegetable life penetrating deeply into the ground take from the soil and the underground reservoirs much water which otherwise would ultimately reach the stream. After a considerable period of dry weather one has only to make a comparatively shallow excavation in the field and forests to ascertain how greatly the deep roots from the forest trees drain the soil of its water to considerable depths for the use of forest growth, and consume instead of conserve the supply they are said to store.

Much stress is sometimes laid on the reservoirs provided by the forest beds which are said to conserve the rainfall and to regulate runoff. Such reservoirs are largely ideal and are ordinarily of small relative importance. The investigator will search in vain in the forest bed for the

1 Bulletin No. 7, Forestry Div. U. S. Dept. Agriculture, p. 131.

stored water which is claimed to regulate and augment the flow of streams.

There is no mystery to the engineer as to the actual reservoirs which supply the normal streams. A visit to the lakes and swamps will show a quantity of water therein contained which is manifest and not to be questioned. An excavation into the drainage area will uncover the underground sand and gravel and the water is there in great quantities. Its presence or importance can not be questioned. The surface waters from lakes and ponds, and the ground waters from sands and gravel are well known resources from which extensive public and private water supplies are often obtained, but the history of water supply engineering fails to furnish one instance where a forested area, as such, has been given any consideration as the possible source of a public water supply.

There is no question but that forests and vegetation on abrupt slopes of certain character prevent denudation and hence may preserve certain deposits which act as underground storage. By the preservation of such vegetation, these deposits may be kept from being washed to river channels, and local conditions of storage are thus maintained better than would be the case when cultivation is attempted under improper conditions. In such cases, forests or other vegetation may have an important but indirect local effect on navigation and river improvements or maintenance, but such efforts are purely local and do not in general appertain to all forest areas.

203. The Character of the Storage on the Drainage Area.—The important factors are the nature and extent of

A. Surface storage, consisting of lakes, ponds, marshes and swamps.

B. Ground storage, consisting of gravel, sand, and other similar pervious deposits.

C. Artificial storage, consisting of waters impounded by dams for various useful purposes.

The natural storage of any drainage area and the possibilities of artificial storage depend principally upon its topography and geology. Storage equalizes flow, although the withdrawal of precipitation by snow or ice storage in northern areas often reduces winter flow to the minimum for the year. Both surface and subsurface storage sometimes hold the water from the streams at times when it might be advantageously used. Storage, while essential to regulation, is not always an advantage to immediate flow conditions.

A. Surface Storage.—The presence of surface storage, ponds, lakes,

swamps, marshes, depends on incomplete drainage conditions and the existence of depressions with impermeable beds and restricted outlets. Such conditions tend to regulate the flood flows from drainage areas and to retard the flow of storm waters, delivering them more slowly than would occur from other areas. The effect of lakes and swamps is to reduce the flood peaks and prolong the high water period. Unless very considerable or unless augmented by extensive pervious deposits,

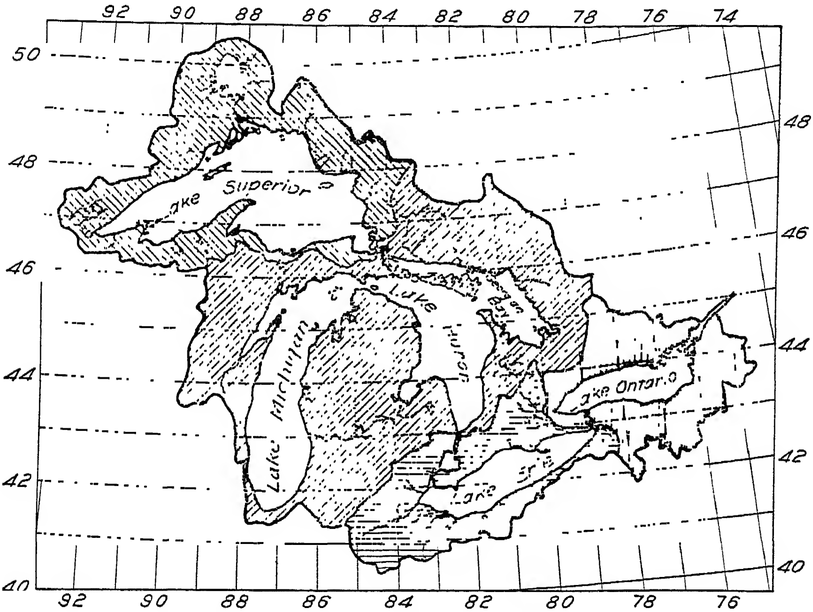

FIG. 268.—Drainage Area of the Great Lakes.

their influence on the low flow of extreme dry periods is not particularly advantageous without artificial regulation. The evaporation from such swamp and marsh areas, and similarly exposed bodies of water, is considerable and reduces total runoff.

The rivers flowing from the Great Lakes of North America are an important example of the effects of natural surface storage on the regulation and flow of streams. The ratio of lake surface to drainage area (see Fig. 268), on these areas is about 33 per cent. for the entire system, and the ratio of average annual discharge to mean annual rainfall is about 37 per cent. This is less than the average ratio of discharge to rainfall of many streams in their immediate vicinity, and the reduction is doubtless due to the great evaporation from the free water surface of the lakes.

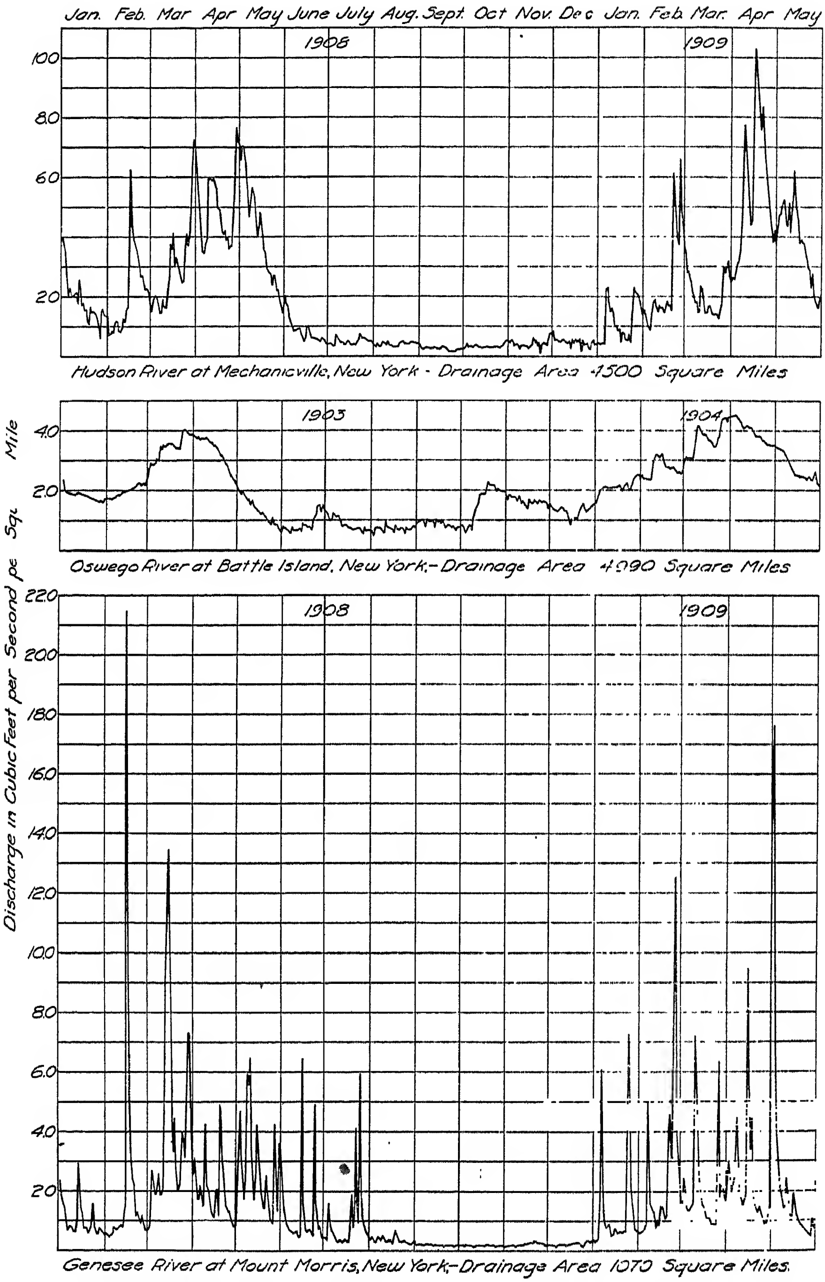

FIG. 269.—Hydrographs of Certain New York Streams.

The effect of surface storage on the flow of streams is well shown by (Fig. 269, page 458), a comparison of the hydrographs of the Hudson, Oswego and Genesee Rivers of New York State. The Hudson River flows from a drainage area (see Fig. 270) having numerous small moraine lakes providing moderate storage. The drainage area of the Oswego River (see Fig. 271, page 460) has an unusual amount of

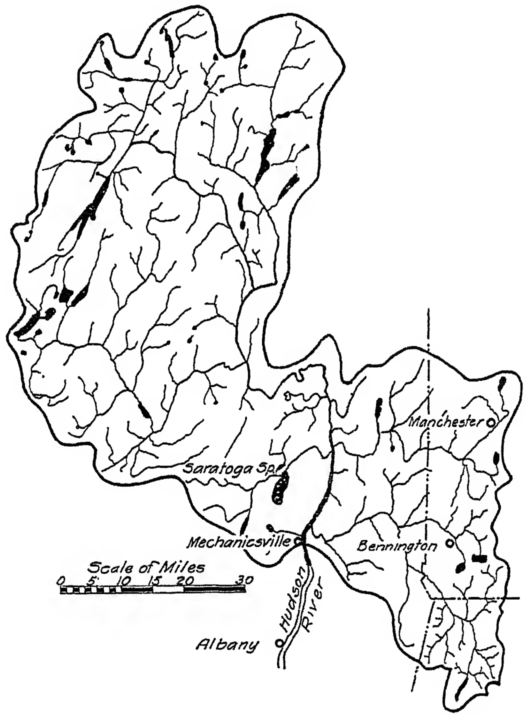

FIG. 270.—Drainage Area of the Hudson River.

storage in the numerous lakes of central New York. The Genesee River (see Fig. 272, page 461) has only a limited amount of surface storage. A part of the difference in the flow of these streams may be due to underground storage, although this factor is believed in these cases to be subordinate to surface storage.

B. Sub-Surface Storage.—Extensive pervious deposits on a drainage area generally produce a high degree of regularity in the flow of a stream. On drainage areas where such pervious deposits are extensively developed, the rainfall, especially if the surface be uncovered by vegetation, is rapidly absorbed, becomes a part of the ground water,

flows slowly toward the stream and, dependent upon the character of the deposit, reaches the stream only after a lapse of days or perhaps months. As the ground water becomes filled the gradient becomes steeper and the rapidity of its flow is increased. Heavy rainfalls on a

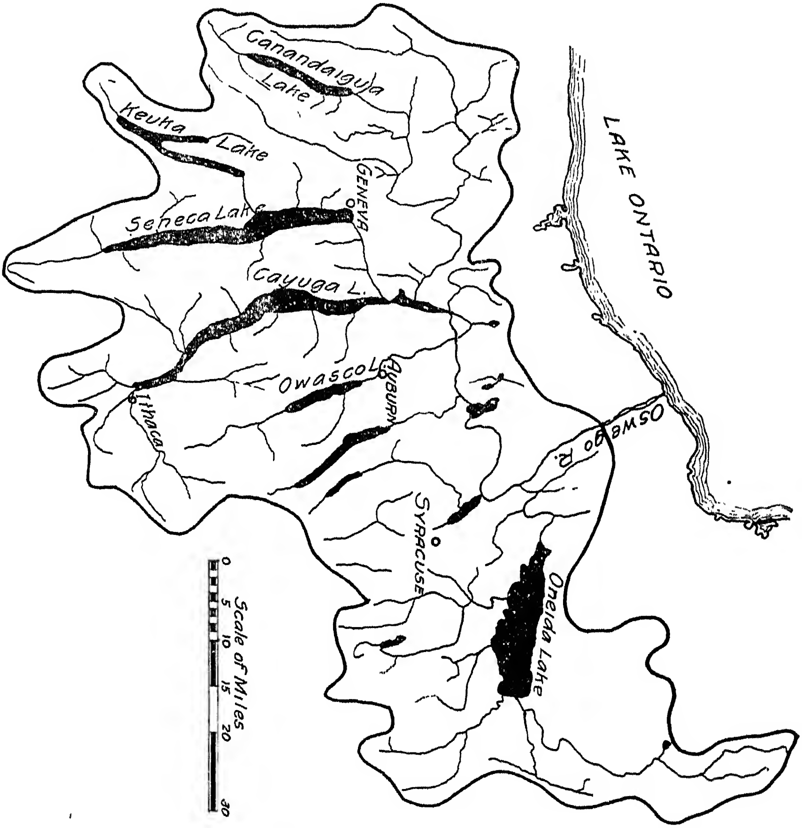

FIG. 271.—Drainage Area of the Oswego River.

pervious drainage area therefore will considerably increase the velocity of the ground water flow and hence augment the flow of the streams to a greater extent during or following such periods. As time passes after the occurrence of rains, the gradient will slowly decrease as the water drains from the pervious deposits into the stream, the velocity and quantity of flow become less, and the stream flow gradually decreases. The decrease, however, is not rapid and a sufficient quantity is often held in storage until further rainfalls augment the stored ground water and again increase the stream flow. With high ground water,

such a stream may frequently flow for several months without any additional rainfall, and the flow is commonly regulated to a greater degree by this means than by any other natural condition on the drainage area. The flow from such areas is usually a comparatively large percentage of the total rainfall.

Ground storage in gravels and sand, or other pervious deposits, removes to a considerable extent all of the water reaching them from the immediate influence of evaporation and stores them under the very best conditions for the future supply of the stream.

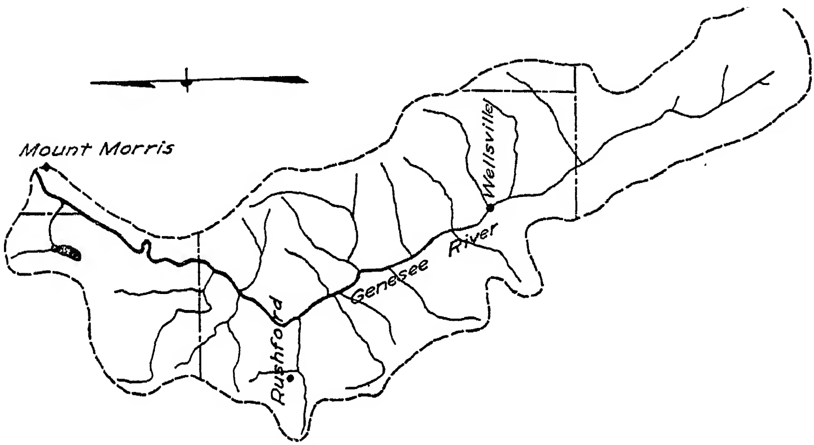

FIG. 272.—Drainage Area of the Genesee River.

The difference in the effect of surface and underground storage is quite well illustrated by a comparison of the Black and Wisconsin Rivers of Wisconsin, with the Manistee River of Michigan. (See Fig. 273, page 462.) The Wisconsin River drainage above Merrill, Wisconsin, has numerous moraine lakes and several artificial reservoirs to store water for power purposes. (See Fig. 200, page 339.) The Black River above Neillsville, Wisconsin, has little storage. The Manistee River has little surface storage, but its drainage area is largely of sand and the regularity of the flow is remarkable.

C. Artificial Storage.—Artificial storage created and controlled is usually surface storage and is open to the objections previously mentioned. It has the advantage of permitting the use of the stored water when and as it is needed, and the entire withdrawal of the supply at other times provided the control is sufficiently extensive. Storage, when introduced on a drainage area, can be used for equalizing flow of

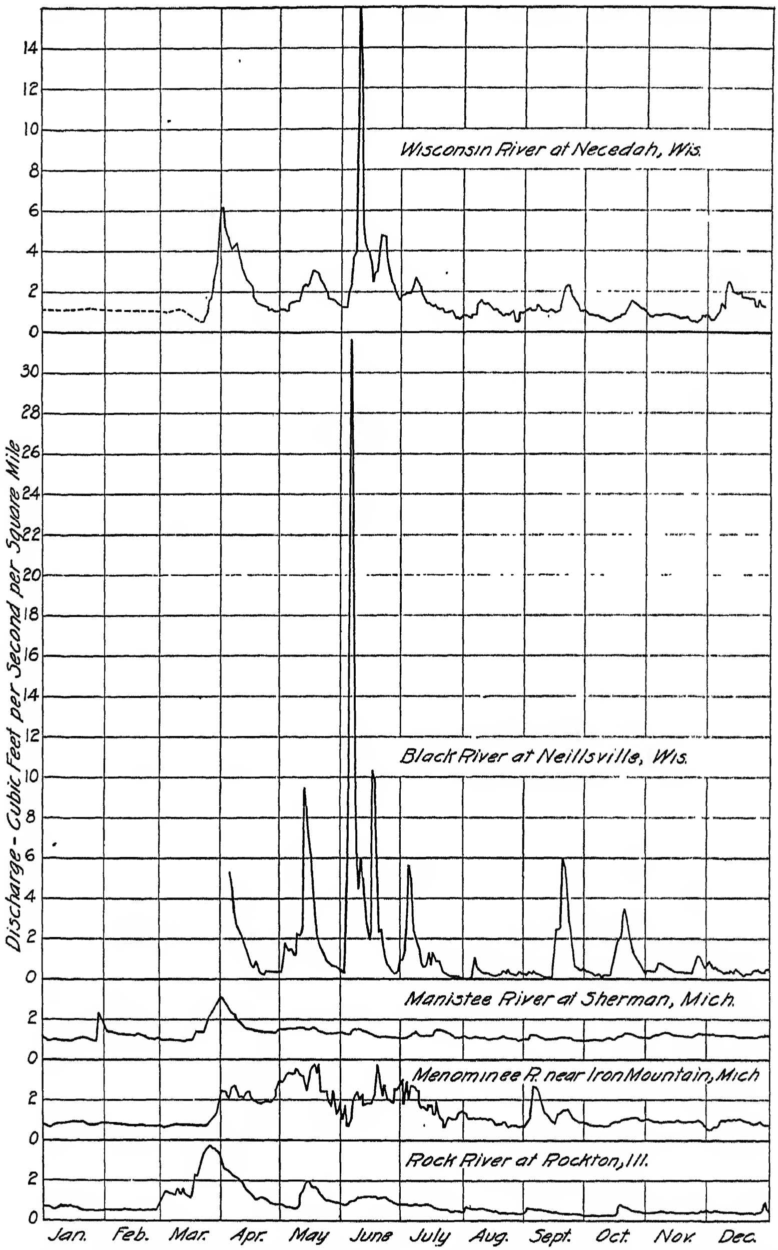

FIG. 273.—Comparative Hydrographs of Certain Wisconsin and Michigan Rivers.

the main stream only with certain points and purposes in view. Frequently, where water is stored for various purposes, such as navigation and power purposes, its use for one purpose is found to be antagonistic to other uses.

Figure 274, page 464, shows the ideal regulation of the Hudson River based on a proposed extensive reservoir system and on the stream flow for the years of 1908 and 1909. It may readily be appreciated that the regulation secured by such means during a term of years will vary greatly, depending upon the increase or decrease in the annual runoff and on the distribution of the same.

An example of the manner in which adequate storage facilities may reduce the flood peak is afforded by the Shoshone Dam near Cody, Wyoming. The normal flow of the river is discharged through two 48-inch circular pipes at the base of the dam, which is 295 feet high from foundation to spillway, and impounds some 256,000 acre feet of water. As the flood waters due to the melting snow come down in June, the reservoir begins to fill and the discharge through the sluices slowly increases with the head, usually in August the water in the river above the dam begins to grow less than the discharge through the pipes and by November the reservoir is again empty. The effect is to extend the high water flow over the entire summer and wholly to do away with the flood conditions as there has seldom been sufficient water to cause a discharge over the spillway.

204. **Artificial Use and Control of Streams.**—When the waters of a stream are diverted or used, all or in part, an effect on the stream flow below the point of use is obvious. Such cases may include irrigation, public water supplies, and supplies for navigation canals. Furthermore the waters may be controlled: *a*. For water power purposes; *b*. For storage to utilize flood flows during low water periods or to mitigate high water conditions in the lower river; *c*. For the improvement of navigation by the construction of wing dams and jetties; *d*. For preventing overflow by constructing dikes and levees which restrict the river to a channel section; and *e*. For other public or private conveniences or profit by various other encroachments upon the waterway often made without intentional interference with the régime of the stream.

The construction of dams in a stream for power purposes affects the regularity of flow at every point below the dam, unless offset by a regulated discharge. The closing of a power plant, even with water going over the spillway of the dam, will cause a considerable decrease in flow below, as the pond above must fill before sufficient head is gained to

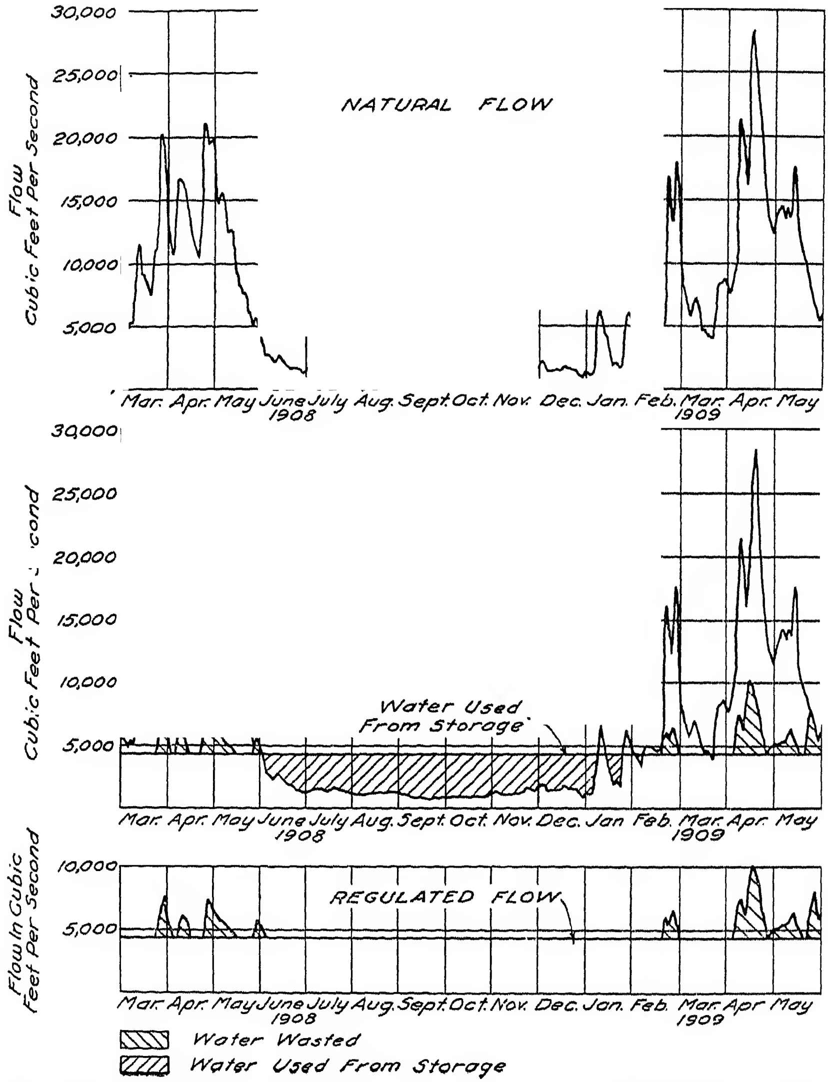

FIG. 274.—Ideal Effect of Storage on the Flow of the Hudson River. After N. Y. State Water Commission, 1910.

produce the same discharge. Numerous installations of this kind on a stream often seriously interfere with the regularity of flow below them, and may prove disadvantageous to navigation. (See Fig. 275, page 465.)

The diking of channels to prevent overflow of lands often seriously

affects flood heights at and above the lands diked, as the water which was formerly stored by overflow is forced through the restricted channel and more head is therefore necessary. The levees of the Mississippi River at and below Memphis, Tennessee, have caused the flood peaks at Memphis to rise more than eight feet above their former level.

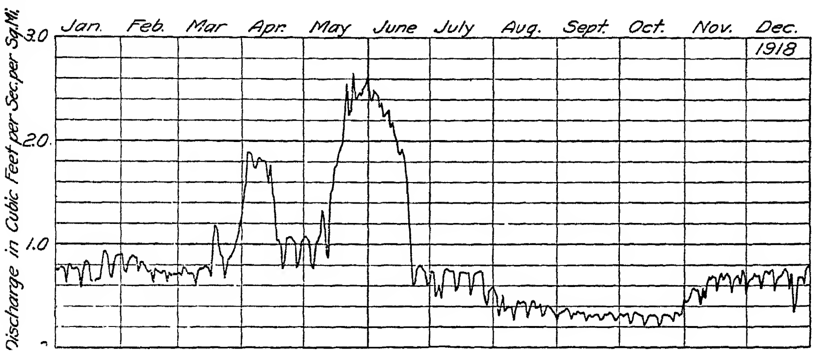

FIG. 275.—Hydrograph of Fox River at Rapids Croche Dam, Showing Effect on Flow of Lower River of Sunday Closing of Water Powers.

FIG. 276.—Obstructions in the Rock River at Janesville, Wis.

It is necessary only to point out the radical effect of the diversion of water for irrigation, water supply and the feeding of navigation canals. Such effects are greater or less in accordance with the proportion of water removed from the stream, and the amount returned thereto by the seepage from irrigated lands, from irrigation ditches and the discharge of waste weirs and overflows from canals.

Wing dams, jetties, and other navigation works are built to improve channel conditions without materially increasing the head at flood stages. The construction of bridge piers and abutments, the filling of low lands and other encroachments on the stream channel, while not intended to interfere with floods, often tend to produce higher flood peaks both by direct contraction of the channel and the opportunities of still greater contraction by the chance afforded for collecting and retaining drift. The obstruction of channels caused by the construction of buildings over streams in cities where land values are high, sometimes results in conditions which may prove serious in extreme floods. (Fig. 276, page 465.) Such obstructions in Mill Creek at Erie, Pennsylvania, occasioned the great flood losses at that place in August, 1915.[2]

205. Conditions Favorable to Maximum Water Supply and Equalized Flow of Streams.—Case I. The following conditions are favorable to maximum equalized flow:

A. Drainage Area:

a. The drainage area must have an impervious bed of such a geological character that no water can sink into its mass and be conducted beyond the drainage boundaries to other areas, but it must be of such nature and capacity that all the precipitation received and not necessarily lost by evaporation shall pass ultimately to the river channel.

b. The surface slope must be slight so that little surface flow will take place even with intense precipitation.

c. The larger the drainage area, the less the opportunity for a general intense precipitation which sometimes occurs on small areas, and the less the variation in flow under varying conditions of precipitation throughout the year.

d. The temperature on the drainage area must be moderate, cool to reduce evaporating effects, and above freezing so that the surface may never become impervious through the formation of ice, or receive precipitation as snow, with resulting loss from evaporation.

B. Precipitation:

a. The larger and more uniform the distribution of the annual precipitation, the greater the stream flow and the more perfect its equalization.

[2] Eng. News, August 12, 1915; also Eng. Record, August 14, 1915.

b. The precipitation should be moderate in intensity so that it may be absorbed by a pervious surface and without surface flow, but never so light as to result simply in the moistening of the surface, with consequent loss by evaporation of the small precipitation thus received.

c. For maximum water supply, maximum precipitation or high precipitation, with other favorable conditions, is essential. Whatever the precipitation may be, the maximum amount of runoff will result when the maximum proportion of the precipitation is preserved to the stream. For equalized stream flow, a uniform distribution of precipitation through each and every year is most favorable, and any variation in precipitation must be offset by inter-precipitation storage which, however, must not result in undue evaporation.

C. Storage:

a. In order that evaporation may be a minimum and hence the water supply a maximum, there must be no surface storage, and the river channel must be comparatively deep and narrow, with a minimum exposed water surface.

b. To provide storage and equalize the otherwise irregular stream flow due to the natural irregularity in the occurrence of precipitation, the impervious bed of the drainage area must be covered deeply with pervious sandstones or sands, not so coarse as to permit rapid flow through their structure but coarse enough to receive the rainfall rapidly into their mass in order to avoid evaporating influences at the surface and to convey the waters deep enough so that capillary attraction will not draw them to the surface and subject them to evaporation. The surface must be free from vegetation and be unobstructed by roots which would produce similar effects.

For conditions favorable to maximum runoff and equalized flow essentially as described above, consider a broad deep impervious rock valley deeply filled with sand and gravel, the surface devoid of vegetation and with the stream meandering through the center of the pervious plain. The rain falling on this area will sink rapidly into the pervious deposits and move slowly toward the river. Little of the water will be lost in evaporation because the rainfall will immediately sink below the surface and reach the ground water where it is not subject to evapora-

tion effects. The great deposit of sand and gravel will store the water, retard its flow and permit it to move slowly towards the stream which will be fed with great uniformity, and while the ratio of rainfall to runoff in such a stream will be high, it will at the same time be distributed with considerable uniformity throughout the year and the stream will be perennial. These conditions will result in equalized flow, the degree of uniformity depending upon the perfection of development of the dominating factors mentioned above. There are few examples of extremely favorable conditions of this character. However, an illustration of the results of the occurrence of such factors to a high degree is shown by the hydrographs of the Manistee River of Michigan which flows through a sandy country where underground storage is highly developed. (See Fig. 273, page 462.)

206. Conditions Favorable to Maximum Variation in Water Supply of Streams.—Case II. For the maximum variation in the water supply of streams, the extreme case occurs when torrential flows, following heavy precipitation, are succeeded by dry stream beds shortly after precipitation has ceased. The following conditions are favorable to maximum irregularities in flow:

A. Drainage Area:

a. In this case the conditions of maximum quantity and intensity of runoff require an impervious rocky drainage area.

b. The drainage area must have a steep channel and abrupt slopes to the divide. The rock surface must be smooth, and both main and lateral channels unobstructed.

c. No soil or mantle deposits, no vegetation, no storage, surface or subsurface, must exist to obstruct or delay surface flow if the maximum torrential stream flow is to result.

d. The temperature must be mild to avoid storage in the form of ice or snow, but not too warm or evaporation will reduce runoff.

e. The smaller the area, the more surely will areas of intense rainfall cover the entire drainage area and produce extreme conditions.

B. Precipitation:

a. The precipitation must be concentrated in a limited rainy season with continuous downpours, followed by long continued droughts. Light rain would increase evaporation and decrease the total discharge.

A modification of the above conditions, leading in some cases to equal or more extreme conditions, might be occasioned by great deposits of snow during winter months followed by rapidly rising temperatures on the advent of spring when the combination of torrential rains and melting snow might result in maximum runoff.

Under the above conditions the heavy precipitation of intense storms accompanied perhaps by the waters from melting snows will flow rapidly and unimpeded down the smooth and abrupt slopes to the channel and rush down its steep gradient to its outlet, leaving a dry stream bed soon after the rain has ceased. The predominating influence of factors tending to irregularity of flow are shown by the hydrograph of the Genesee River, Figure 269, page 458. This example is not an extreme case, for this stream is seldom or never entirely dry; its hydrograph shows the resulting conditions somewhat better than in the case of streams which entirely cease to flow at certain times in the year.

207. **Conditions Favorable to Minimum Runoff.**—Case III. The following conditions are favorable to minimum runoff:

A. Drainage Area:

- a. A pervious soil over a pervious rock bed from which the seepage waters will be permanently lost to the stream.
- b. A low, flat drainage area largely covered by shallow swamps, filled with vegetation, from which the flow will be sluggish and the evaporation large.
- c. High temperature and strong winds, to increase evaporation, reduce humidity, and rapidly remove the humid atmosphere.

B. Precipitation:

- a. A small rainfall occurring in light showers, well distributed throughout the year.

An excessive development of these conditions may result in no flow from a given area.

Such conditions are not rare but as a rule are confined to very small drainage areas. There are numerous examples of such conditions found in Wisconsin and these examples are of two classes:

1. Small sinks in sandy soil from which the rainfall partially evaporates and partially sinks into the soil and flows to the main drainage channel of the general drainage area on which the sink is a local development. Similar sinks are also found in many limestone regions. In both cases seepage may be a considerable factor in rainfall disposal.

2. Small depressions containing lakes which occupy a large proportion of the drainage area. In such cases seepage is a minimum and evaporation a maximum cause of rainfall disposal.

208. Discussion of Extreme Conditions.— In Sec. 207, Case III, are illustrated the limiting conditions of no supply and this case needs no further discussion. Cases I and II embrace the extreme conditions of maximum water supply and uniformity of stream flow on the one hand (Sec. 205) and of maximum irregularity on the other hand (Sec. 206). In either case increased drainage area tends to greater regularity of flow but almost any other change or modification of whatever nature will disturb the condition and produce opposite effects in the two cases considered. The introduction of surface storage on these areas will increase evaporation in both cases, and hence will decrease total discharge; but it will decrease regularity in Case I, while it will increase it in Case II.

In Case I the occurrence of forests or vegetation of any kind on the drainage area will obstruct the pervious surface deposits and reduce the free access of water. The lighter rains will be kept entirely from the soil and evaporated from the surfaces of leaves. The forest bed will hold the moisture from the soil and conserve it for plant use. The roots will draw the moisture of the pervious soil from considerable depths. In each case a reduction in flow and a tendency to irregularities will result. In Case II the occurrence of forests on the impervious area, the forest bed, the vegetable fibre, the cracks opened by the roots, all offer both obstruction and limited storage and, while slightly reducing the discharge, tend to equalize flow.

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CHAPTER XVII

VARIATIONS IN RUNOFF OR STREAM DISCHARGE

209. Importance of a Knowledge of the Variation in Stream Flow.—The hydrographs previously discussed indicate in general great diversities in the discharge:

1. Of different streams.
2. Of the same streams during different years.
3. Of the same streams during different seasons of the same year.

These differences have marked influences on the availability of each stream for utilitarian purposes depending upon these variations and the uses to which the stream may be applied.

In order to make the use of a stream practicable for the purposes of a public water supply, navigation, water power or irrigation, it must be possible to secure a sufficient supply of water as needed and at a cost low enough to make the project financially feasible, otherwise the project should be abandoned. In every project the needs or demands for water and the supply are both more or less variable and are affected by the seasons, the climate, and by many other conditions. When only small supplies are to be taken from large lakes or rivers, the variations in runoff may be of little relative importance; but when, as in many cases, the source of supply is to be developed to the maximum practicable extent, the problem of conserving and utilizing the irregular flow of a stream so that it may be made available at the time and in the quantity needed for a given purpose, is important. Every problem of this kind is essentially different from every other similar problem and must be considered by itself and in the light of all modifying influences. In considering such uses therefore any examples are only illustrative of special conditions and in every case the engineer must investigate for himself the nature of the demands of his project and the possible supply available from the particular source from which such demands must be met.

210. Consideration of Public Water Supplies.—In the consideration of water supplies for most projects, not only the present but the future demands, must receive attention. The water needed for a public supply will increase with the growth of population; it will vary from day to day with the season, with the humidity and with the temperature; it will be less at night than in day time. In every problem

these factors and often many others must be considered in connection with the source of supply and in the plans for its development.

Fig. 277 shows the variation in both annual and monthly pumpage at Milwaukee, Wisconsin, together with the growth in population supplied. As Milwaukee draws its supply from Lake Michigan and that source for the purpose is unlimited, these variations are of importance only in the design of the system; but if on account of gross pollution of the lake, Milwaukee was obliged to turn for a supply to upland streams, the future increased demands and their variations together with the variations in the flow of the stream considered would be of

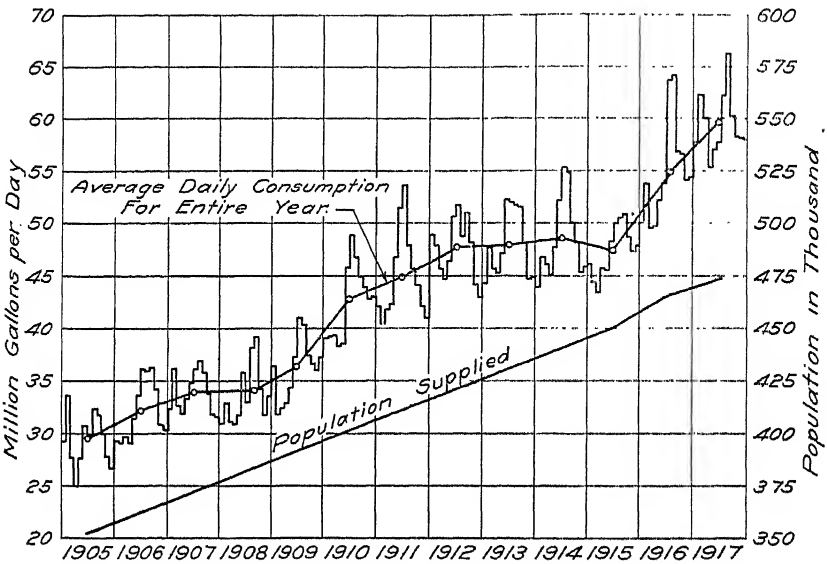

FIG. 277.—Variations in Monthly and Annual Pumpage at Milwaukee, Wis.

great importance in considering the adequacy of such sources and the works needed to make the source useful to its maximum limits.

211. **Consideration of Supplies for Power Purposes.**—For water power purposes studies of available supply and probable demand are not less important than for other projects. Fig. 278 shows the flow of the Peshtigo River, the power output of the plant (see Frontispiece), the water stored and drawn from storage, the fluctuations in the reservoir surface and head, and the water wasted. To determine the practicability of utilizing the irregular flow of a stream for water power purposes, a study of its hydrographs, of the available heads, of the probable demand for power, of the available pondage or storage and of their economic relations is necessary.

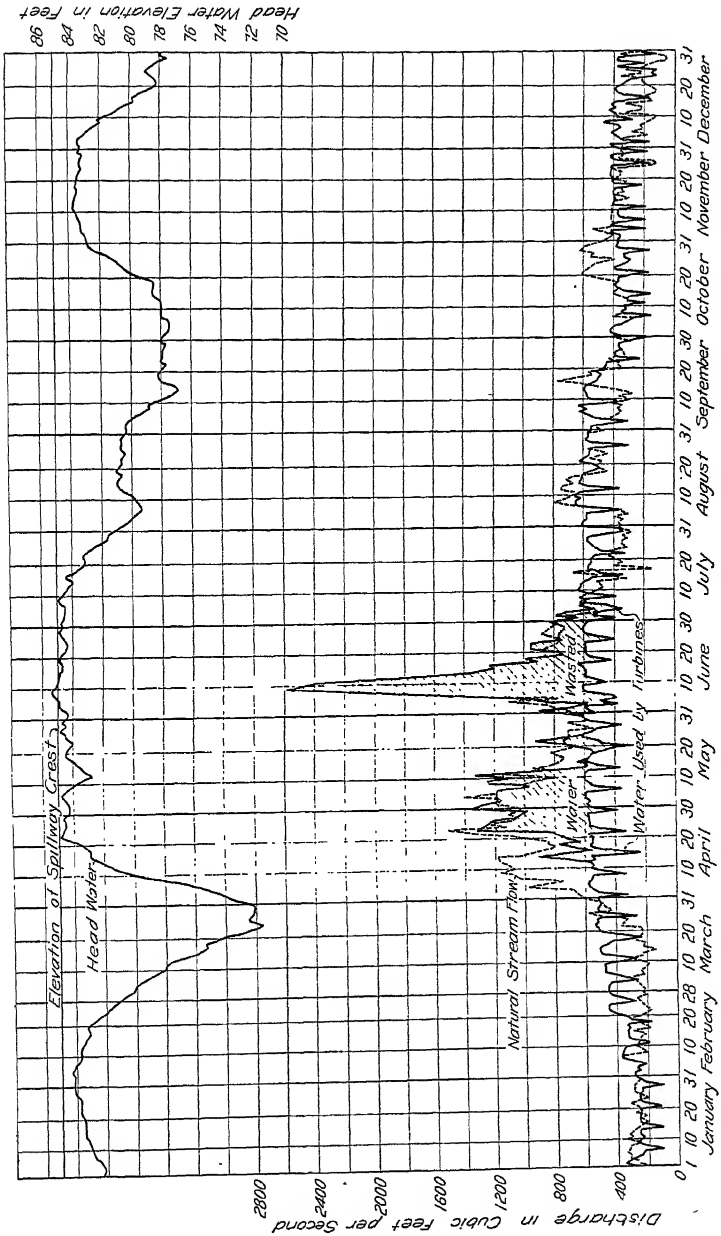

FIG. 278.—Daily Variations in Water used and in other Conditions at the High Falls Hydro Electric Plant in 1917.

212. **Consideration of Supplies for Irrigation.**—For irrigation purposes comparisons of supply and use are also essential. In many cases irrigation supplies are needed for only certain months in the year

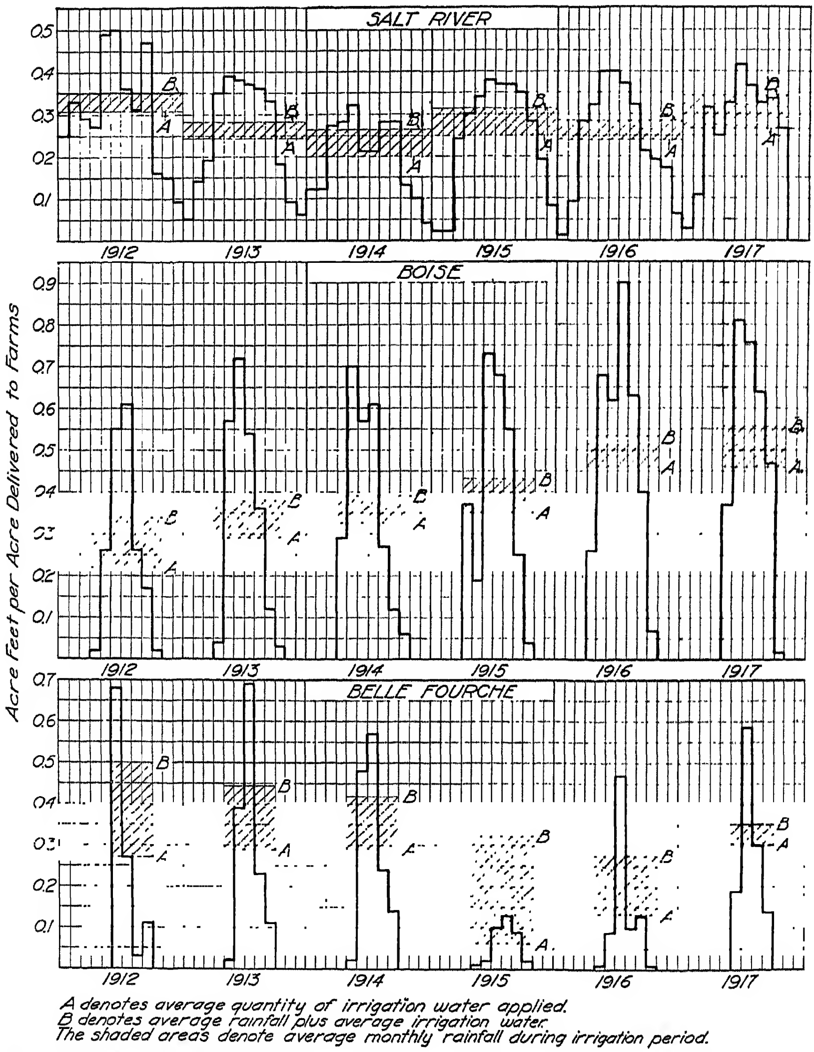

FIG. 279.—Monthly Variations in Water used on Three Irrigation Projects.

and no water is used during the remaining months. Fig. 279 shows the variation in the monthly and annual use of water on three irrigation projects of the United States Reclamation Service for the years 1912 to 1917 inclusive. On the Salt River Project in Arizona water

is used to some extent during every month of the year, while on other projects water is used for only a portion of the year.[1] The demand for water will necessarily increase with the increase in area under cultivation unless greater economies in the use of water can be successfully introduced or an increased rainfall is experienced during the irrigation season. The size of the project should be limited to the areas for which water can be made available. Fig. 280 shows the areas irrigated each year on these projects, the total amount of water used, and the rainfall during the irrigation season. An unusual rainfall

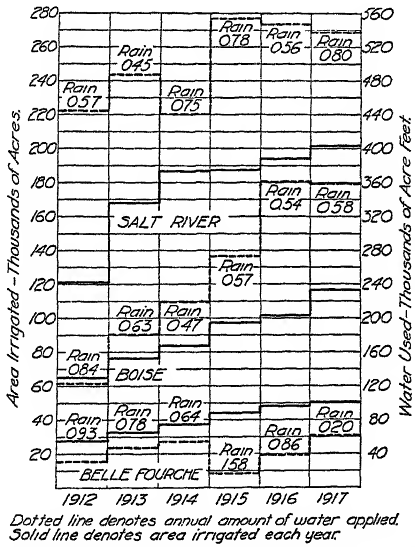

FIG. 280.—Water used and Area Irrigated on Three Irrigation Projects.

on the Belle Fourche Project during the irrigation season of 1915 affected the amount of irrigation water used, as shown in Figs 279 and 280.

213. **Consideration of Supplies for Other Uses.**—For navigation purposes water is used in northern climates for only certain periods during the open season when navigation is possible. For the remaining portion of the year ice prevents the operation of boats and the supply of water can be stored and held for navigation service if sufficient storage is available. In southern waters navigation may be continuous throughout the year and a different demand results. In each case the effect of climate and other factors of demand change the problem, but in every case the problem is that of supply and demand

[1] Reclamation Record, November, 1918.

and involves the determination of the variations and the methods necessary to equalize them.

214. **Physical Variables in Engineering Problems.**—In mathematics and other sciences certain principles defining the relations of cause and effect can be deduced which, when all extraneous influences can be eliminated, are absolute and universal. When, however, such principles are applied to engineering calculations the influences of varying physical conditions frequently make the application of such principles obscure, and the effects which will obtain cannot be accurately calculated from the simple principles which are obviously involved. Under these conditions a knowledge of the fundamental principles is still valuable for such principles frequently serve as the only guide for the engineer in his calculations even when they do not permit of an exact quantitative determination of results. To compensate for the unknown effect of the physical variables involved, factors of safety may be used in all engineering design.

In the complicated problems of hydrology the underlying principles are obscure, for extraneous influences can seldom be so eliminated as to establish relations that are universally applicable. The predominating influences are not always the same, and relations which seem obvious under one set of conditions appear absurd under conditions that are radically dissimilar. The determination of runoff is therefore not a simple problem but is in fact exceedingly complicated. Nevertheless, it is believed that by intelligent investigation and study such problems can be solved as accurately as most other engineering problems and that by the introduction of reasonable factors of safety, such solutions can be safely used as a basis for hydraulic design.

The attempt in the following pages to outline underlying principles of runoff is for the purpose of calling the attention of the engineer to:

1st. The complicated principles involved.

2d. The danger of the unwarranted assumption of simple relations which do not exist.

3d. The necessity of making an intelligent investigation of the many factors that modify the results which will obtain before any dependable conclusions can be reached.

The errors that often obtain in runoff estimates arise from the omissions of factors of safety and by attempts, often without proper investigation, to fix exactly the maximum or minimum flows or the mean daily, monthly or annual runoff. No engineering estimates can be made that are more than approximate, and allowances must be introduced to cover the ignorance of exact physical conditions.

In the design of structures the maximum load should seldom exceed 1-3 or at most 1-2 of the normal limit of elasticity of the material used, for the maximum load is often merely an assumption, and the actual elastic limit of the material used is not accurately determined and both are in fact unknown. The structure to be safe must be designed for at least twice the strength that the assumption would seem to require.

In runoff estimates it is impracticable in estimating water supplies to determine the probable minimum supply and to estimate it for safety at only one-half, or in flood protection to estimate the maximum that may possibly occur and then for safety to double the estimate. Such estimates would make hydraulic projects financially impracticable. It is, however, equally irrational to assume even the most dependable estimates of runoff as a safe basis on which to risk the lives or health of the public or the moneys of investors. Reasonable allowances must be made for safety, and the amount of such allowance must depend upon the risk involved and the seriousness of the consequences which will result from possible departures from the estimates made.

215. Measurement of Stream Flow.[2]—The actual measurement of streamflow at the point where it is to be utilized and for a long term of years is the best possible information concerning its runoff. In few cases, however, when the utilization of a stream is first contemplated can sufficient time be taken to secure long time measurements of flow. Nevertheless, it is important when such use is contemplated to establish immediately a gaging station, determine a rating curve, and secure continuous records for as long a period as possible in order to afford some basis for the comparison of the flow of the stream in question with the known flow of adjacent streams from which runoff data may be available for a longer period.

The determination of the flow of a stream is an important but difficult problem. It is evident from the great variations in flow which take place from day to day that any single measurement of the flow is of little importance by itself and has practically no significance. Frequent measurements should be made under different conditions of flow in order to determine the relations between gage heights and quantity, and an accurate long continued and continuous record should be kept in order to ascertain the variations in flow, the usual order of their occurrence, and the dependability of the stream for various purposes. Such a record may be made by single daily observations

[2] For complete discussion of this subject see River Discharge, by J. C. Hoyt and N. C. Grover.

when the stream flow is fairly constant, but should be made by a continuous recording gage whenever possible, especially with irregular streamflow so that all fluctuations of the surface elevation of the stream may be recorded automatically. (See Fig. 55, p. 102.)

The uniform flow of water in channels of regular and fixed cross section and known conditions of roughness can be determined with a high degree of accuracy. In a straight reach of a uniform channel having a uniform slope (Fig. 281) and constant flow, the surface ele-

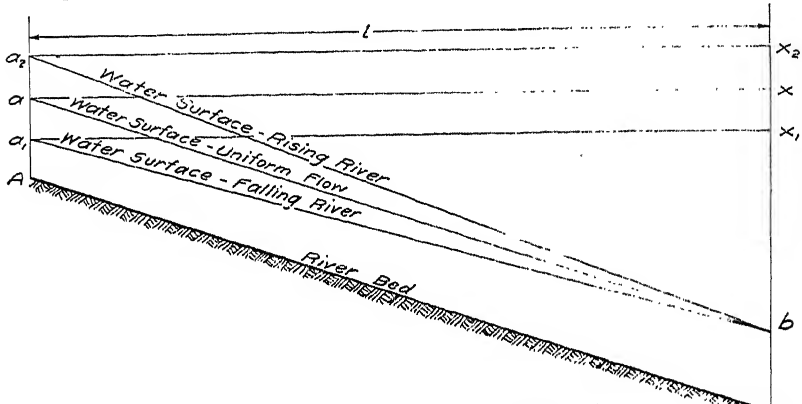

FIG. 281.—Flow in a Uniform Channel.

vation of the stream (a b) will be parallel to the stream bed (A B), and the gage height will always correspond with the same quantity of flow because the fall in the length of channel (l) will remain constant; hence the discharge (q) will always be constant in accordance with the well established principle

$$q = av = ac\sqrt{\frac{a}{p}\frac{h}{l}}$$

in which

q = Flow in cubic feet per second
a = Area of water section in square feet
v = Mean velocity of flow in feet per second
p = Wetted perimeter or wetted cross section in feet
h = bx = Drop in feet in the length of reach
l = Length of reach
c = A coefficient depending upon the roughness and character of the channel

The relations of quantity of constant flow to height of water measured by a fixed gage in any uniform channel can be represented by a uniform curve (Fig. 282 A) which becomes less regular in form with the greater irregularity in the controlling channel section, which controlling section may be some distance below the point at which the gage is established. (Fig. 282 B.) The shape of this curve can be deter-

mined experimentally by measurements at various stages of water in both regular and irregular channels.

It is quite evident, however, that if the flow in the channel be increasing or decreasing (Fig. 281) the surface slope of the stream (a_2b or a_1b) will be measured by the fall (x_2b or x_1b) in the length (l)

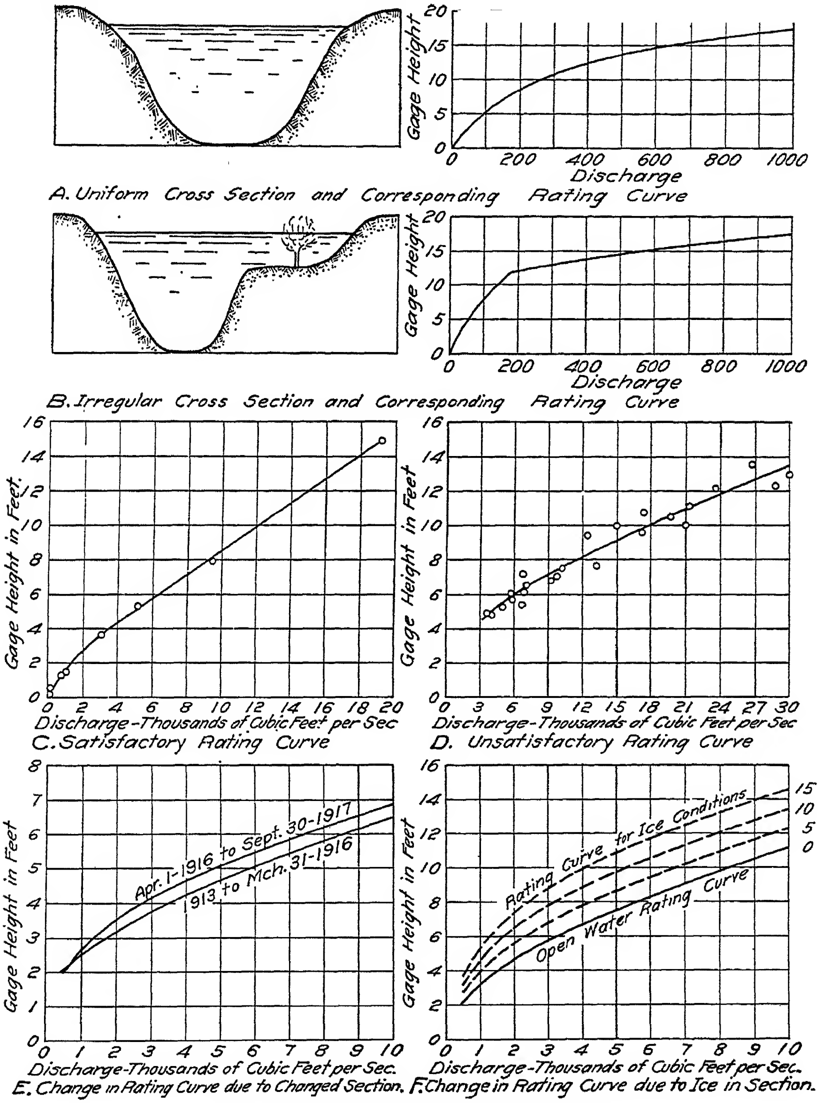

FIG. 282.—Types of Rating Curves.

of the section and while the gage height (Bb) may remain the same for these conditions, the actual discharge through the section will be greater or less than with constant flow.

216. **Difficulties in Stream Measurements.**—Unfortunately for the purpose of stream measurements stream channels vary radically from place to place in section, slope and character of bed, and the flow is not uniform but is constantly changing in quantity and consequently in slope.

In practice, the flow of streams at various times and with various heights of water only approximates that indicated by a rating curve because:

1. The gaging stations may be improperly selected with regard to controlling sections, bends in the channel, obstructions to flow, etc., and thus be incapable of development as a suitable gaging station. (Fig. 282 D.)

2. Measurements may be made with a rising or falling stream when the gradient is greater or less than that corresponding to a uniform flow for the corresponding elevation of the stream. (See Fig. 281.)

3. The measurements from which the curve is established may be in error for accuracy can be attained only by experience and care.

4. Cross sections unless in rock frequently change by scouring or may in any section be changed by the deposition of debris (Fig. 185, p. 327), thus altering the relation of gage height to discharge. (See Fig. 282 E.)

5. The elevation of the water surface of streams may be greatly affected near the outlets by backwater from the rivers into which these streams flow and may at almost any point be affected by backwater resulting from jams of ice or logs, by the lodgment of materials or by the growth of aquatic grass and weeds which increase gage height while they reduce the corresponding stream flow.

6. Even when the section chosen is fixed and satisfactory and the rating curve well established, only continuous gagings by a continuous recording gage will account for all the fluctuations in flow due to normal changes and artificial control of stream flow, and gagings taken only once per day may not fairly represent the flow of the stream for that day. (Fig. 55, p. 102.)

7. Friction of flow is greater with an ice covered river, and a rating curve for ice conditions will differ greatly from the curve for an open channel. (Fig. 282 F.) In northern streams when ice is forming in a channel there is always a period of indefinite flow, for during the

formation of ice the flows must necessarily change from those indicated by the rating curve for open conditions to those indicated by the rating curve for ice conditions, and the same change will take place on the breaking up of the ice in the spring. Such changes cover only a brief period, however, and are less important than other factors mentioned.

Gagings made at dams are frequently in error on account of:

1. Errors in discharge formula or discharge curve used.
2. Leakage around or under the dam.
3. Lack of continuous readings with rapidly varying streams.

For the above reasons many of the published gagings of streams are somewhat in error and consequently misleading. In many of the later stream gagings published by the Hydrographic Branch of the United States Geological Survey the relative reliability of the gagings is indicated. In all cases the gagings should be investigated before they are used as a basis for important conclusions.

217. **Runoff Data and Their Use.**—The Hydrographic Branch of the U. S. Geological Survey has for many years been making observations of runoff on various streams in the United States.[3] The number of gaging stations has gradually been increased as funds have become available, and in many cases the work has been considerably extended by State and private aid. In the earlier days of this work on account of inexperience and the lack of sufficient funds, many records were of more or less doubtful character, but some have been reviewed and rendered more accurate by later studies and investigations and have been republished in a corrected form. In spite of the increasing extent of this work, it is frequently found when a new development is considered, that there are no data bearing directly on the project. Observations have often been made on neighboring streams or at other stations on the same stream, and conclusions must be drawn from the data available. Under these conditions it becomes imperative that runoff relations be investigated in order that such relations may be utilized to modify or confirm the available data for the use of the project under consideration. Unfortunately these relations are necessarily more or less discordant and inexact but this fact is common to all engineering data and should not stand in the way of an attempt to secure the best possible knowledge of the principles from which correct and conservative conclusions may be drawn.

Where meteorological records and stream flow measurements are available the pertinent data most readily obtainable for an area are in

[3] See Water Supply Papers of U. S. Geological Survey.

the order of their importance: runoff (local and comparative), meteorological conditions (precipitation, temperature, wind velocity and humidity), physical conditions (topography, geology, surface and sub-surface storage) and surface culture (forests, vegetation, cultivation, etc.).

Data concerning stream flow can be obtained from various publications and from the local Hydrographic office of the U. S. Geological Survey. Meteorological information can be obtained at the local Weather Bureau and from the publications of the U. S Weather Bureau. Some information concerning physical conditions on a drainage area are often available in various State and United States Geological publications, but detailed data covering topography, geology and the physical condition of the drainage area as regards storage, soil, vegetation, etc., can be obtained only by observation and even then can be only generally known.

The runoff data needed by the engineer in the solution of his various problems may vary greatly. A knowledge of the average annual streamflow is seldom sufficient even with large storage although the equalization of dry periods of several years by storage is sometimes possible. Even in such cases a knowledge of the distribution through the year is desirable at least to the extent of monthly flow. With small storage or with no storage available the flow of a stream from day to day becomes of great importance.

In other problems the extreme conditions of drought or flood or the probable height of water levels are the controlling data and here local records are seldom sufficient, for considering the short time of observation it is seldom safe to conclude that such extremes have been reached, and the engineer must gather information from many other besides local sources as a basis for conservative conclusions.

For comparative purposes the flow from streams of known drainage areas must be available. It is not sufficient that the quantity of discharge of a certain stream be known, for such fact is of no value for comparative purposes unless the number of square miles of drainage area is also known. When comparative hydrographs of the monthly flows of a stream in cubic feet per second per square mile are to be used as a basis for stream flow computations, another doubtful element is introduced by estimating the drainage areas of the two streams that are to be compared. Engineers are cautioned against this source of error in various publications of the Hydrographic Branch of the U. S. Geological Survey.[4]

[4] U. S. Geol. Survey, Water Supply Paper 353, p. 15.

"Even though the monthly means for any station may represent with a high degree of accuracy the quantity of water flowing past the gage, the figures showing discharge per square mile and depth of runoff in inches may be subject to gross errors, which result from including in the measured drainage area large noncontributing districts or omitting estimates of water diverted for irrigation or other use. 'Second feet per square mile' and 'runoff (depth in inches)' have therefore not been computed for streams draining areas in which the annual rainfall is less than 20 inches, nor for streams in which the precipitation exceeds 20 inches if such computations might probably be uncertain and misleading because of the presence of large noncontributing districts in the measured drainage area, of omitting estimates of water diverted for irrigation or other use, or of artificial control or unusual natural control of the flow of the river above the gaging station. All values of 'second-feet per square mile' and 'runoff (depth in inches)' previously published by the United States Geological Survey should be used with extreme caution and such values in this report should be used with care because of possible inherent sources of error not known."

In few cases are available maps sufficiently accurate to permit, with any great degree of accuracy, the determination of the drainage area of large streams. It is therefore evident that not only is measured stream flow subject to more or less error but the drainage area from which it flows is known only approximately and when such data are used for comparative purposes, the exact drainage to which it is applied is also somewhat uncertain.

218. **Variation in the Discharge of Different Streams.**—It is evident that if all things were equal the runoff or discharge per square mile of drainage area for all streams would be the same. In reality great differences occur in different parts of the country in the various factors that affect runoff (Sec. 197) and in consequence there are corresponding great differences in the flow of different streams. Some of these differences are shown by the hydrographs of Figs. 258 to 261, pages 436 to 439 inclusive, where rivers widely separated (Fig. 262) are each represented by a year of high flow and a year of low flow. It should be noted that these hydrographs show the discharge in cubic feet per second (hereinafter abbreviated as second feet or sec. ft.) per square mile of drainage area so that they are strictly comparative except that some of the hydrographs (Nos. 11, 12 and 13) are drawn to a scale ten times greater than the others. The high waters shown by these hydrographs vary from as high as 24 cu. ft. per sec. per square mile to as low as .38 sec. feet per square mile, and the low water flows

vary from as high as one sec. ft. per square mile to as low as .01 sec. ft. per square mile in the years of high flow. In areas widely separated such variations would normally be expected, and it is evident that there is little advantage in a comparative study of the flow of streams not contiguous and physically similiar as a basis for estimating the variations in discharge which may be expected.

In streams that are closely adjoining the comparative discharge may be expected to more nearly agree, but even under such conditions it is evident by a comparison of hydrographs that the physical conditions of the drainage area of various streams in the same state may be so greatly different as to result in large differences in their annual and seasonal discharges. This wide difference is shown by Fig. 269, page 458, which shows the comparative discharge of the Hudson, Oswego and Genesse Rivers in New York State. In the cases just stated the drainage areas are not contiguous, but even when they are nearly so as in the case of the Black, the Wisconsin and the Rock Rivers of Wisconsin (Fig. 273), the conditions are frequently so different that both the high and the low stream flows differ radically in quantity, and the stream flows are not safely comparative. On the other hand it is true that when streams are adjacent and conditions are reasonably similar, a fairly close comparison exists in both the quantity and distribution of their annual flow (Fig. 283), and this agreement is frequently quite as close as is found in the comparison of flow at different stations on the same stream (Fig. 266, p. 449), and often within the limits of the factors of safety which should be applied to runoff estimates.

219. Variation in the Discharge of the Same Stream.—The hydrographs of Figs, 258 to 261 inclusive, show not only the variation in the flow of different streams but also in each case a hydrograph for a year of high flow and for a year of low flow is shown. From these hydrographs therefore an idea can be gained not only of the great difference in flow between different streams widely separated geographically, but also of the great variations that occur in the runoff of individual streams during different years. In long terms of years even greater variations in runoff sometimes occur than are there indicated. To obtain a full knowledge of the variations in the flow of a stream it is essential to study its hydrographs for a long term of years.

The extreme maximum and minimum conditions of stream flow are even more rare in their occurrence than those of maximum and minimum conditons of annual rainfall, and it will be recalled by reference to Fig. 122, page 220, that the extremes of annual rainfall at Boston that occurred in the fifty years prior to 1868 have not recurred in the

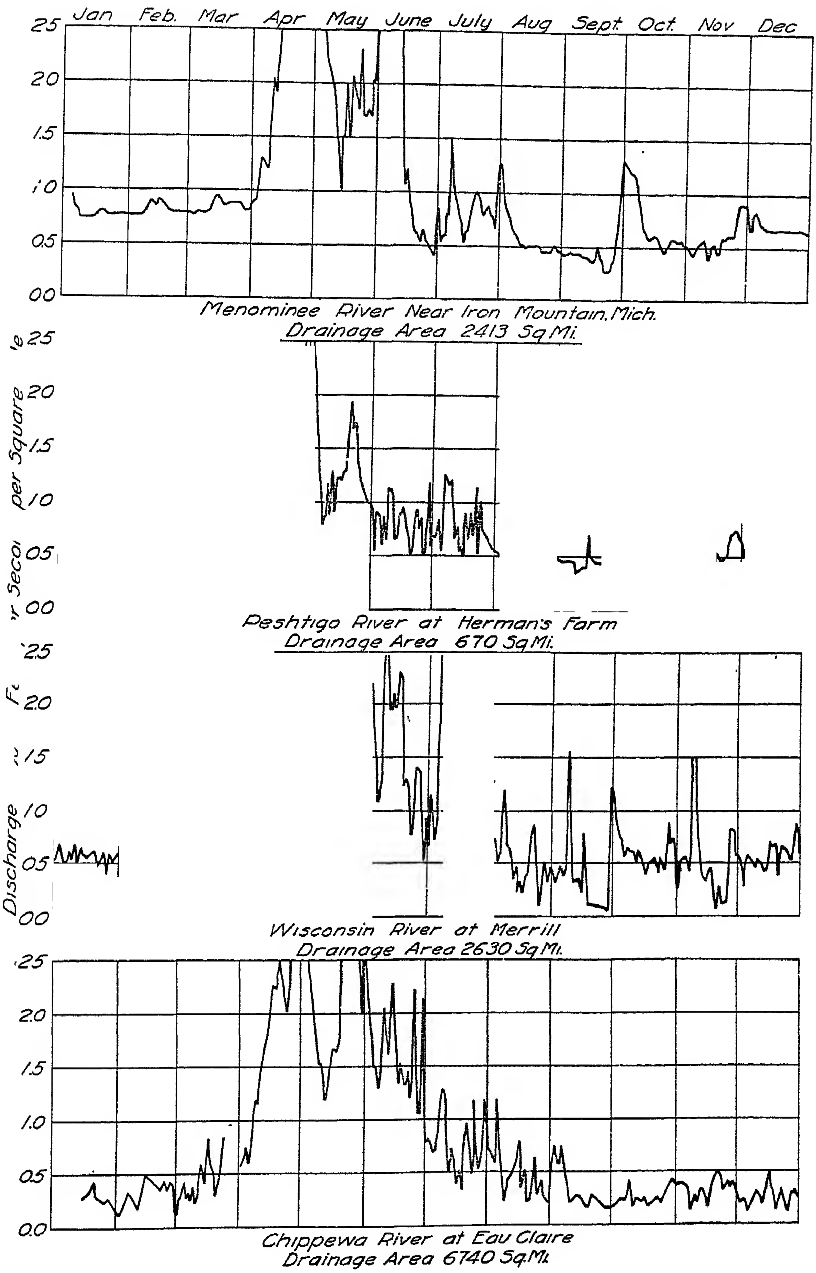

FIG. 283.—Hydrographs of Four Rivers in Wisconsin for 1908.

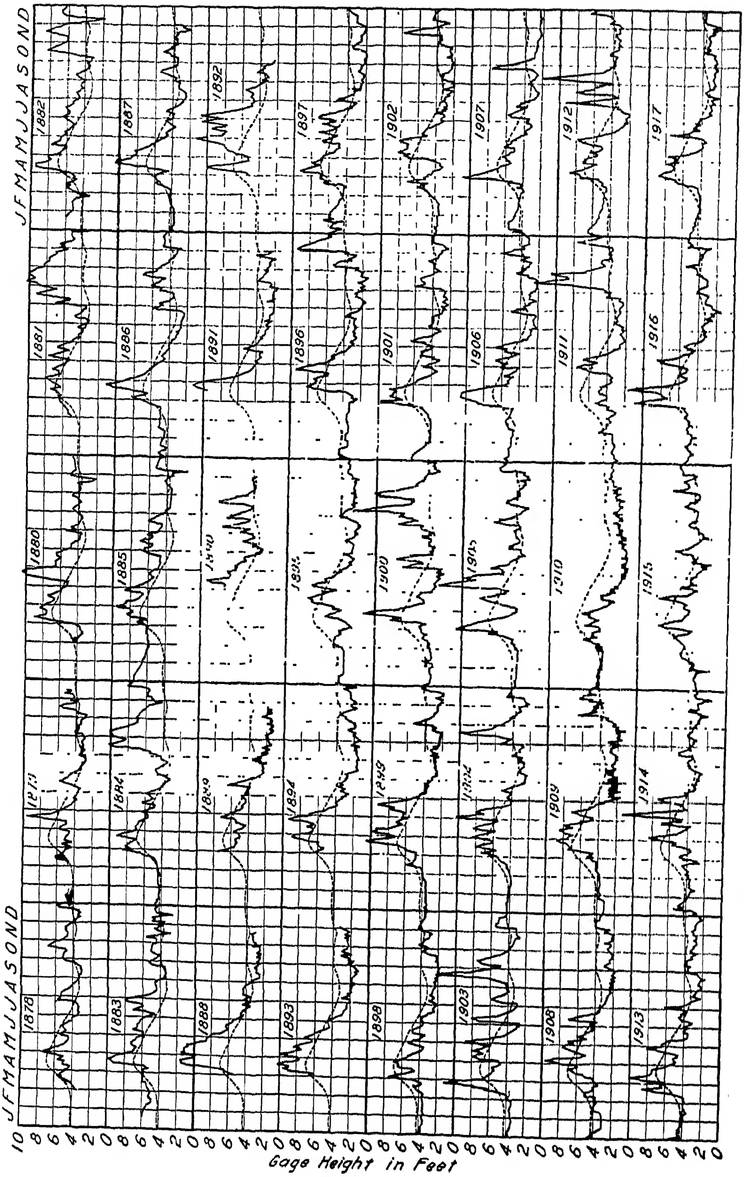

FIG. 284.—Forty years of Gage Heights on the Wisconsin River at Portage, Wis.

fifty years that have since elapsed. As stream flow depends upon the distribution of rainfall even more than on its total amount, and is also affected by various other factors as well, neither the maximum nor minimum stream flow will necessarily occur with extreme conditions of annual rainfall. It may be noted in this connection that the two most serious recorded floods on the Miami River of Ohio occurred in 1805 and 1913, respectively, or one hundred and eight years apart, and it is quite conceivable that even more extreme conditions may occur in that stream at some future time.

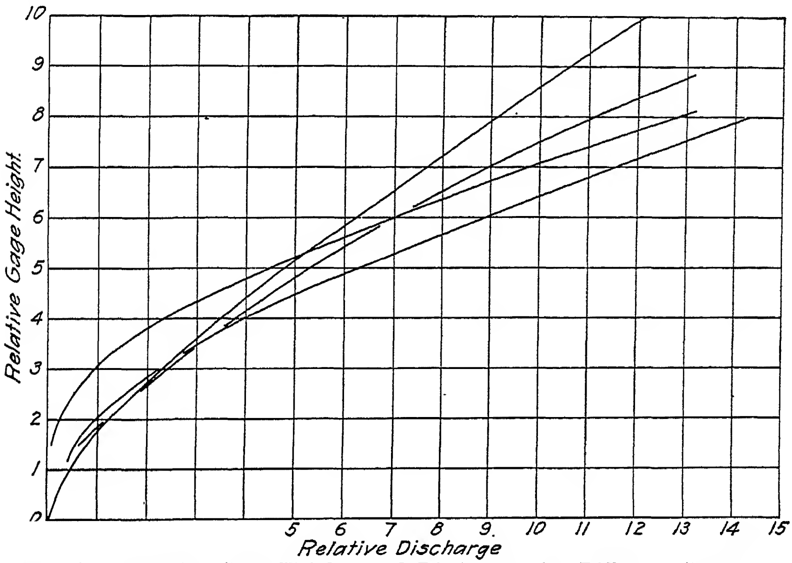

Fig. 285.—Relative Gage Heights and Discharges for Different Streams.

Fig. 284, page 488, shows the gage heights of the Wisconsin River at Portage, Wisconsin, for forty years from 1878 to 1917, inclusive. Gage heights are not directly proportional to stream flow for the discharge increases much more rapidly as shown in Fig. 285, but the gage height frequently furnishes the information desired especially for reclamation and flood protection work and is indicative of the great variations which take place both from year to year and from season to season. In the study of Fig. 282, the occurrence of years of low flow (1905 and 1910) should be noted, also the occasional years of high flow (1881 and 1884) and of exceptional floods (1900 and 1911), and the variation in the time and distribution of high and low water conditions.

220. Seasonal Variations in Streams.—Each of the annual hydrographs which has previously been discussed shows great variations in seasonal runoff. Each hydrograph shows a period of maximum or

flood flow more or less pronounced and also a low water period during which the flow is reduced in most cases to but a small fraction of the maximum flow. The high water discharge is in general due to the occurrence of heavy rainfall or in northern rivers to rising temperatures (Fig. 267, page 452) and the consequent discharge of waters that have been held in storage as ice or snow perhaps for several months and in many cases to a combination of both causes. The low flow is in general due to low rainfall or to the retention of the rainfall from the runoff by evaporation and transpiration which become more active during the growing season. The study of any long series of hydrographs of any stream (Fig. 284) shows that in general the periods of high and low water are somewhat constant but that great variations in their time of occurrences sometimes obtain. Any forecast of such occurrence seems therefore quite indefinite and can be accomplished, if at all. only by a study of the rainfall-runoff relations of the past together with the many other physical conditions that modify such relations.

221. **Rainfall and Runoff.**—As rainfall is the primary cause of runoff, the flow of a stream is naturally expected to increase or decrease with the rainfall, and in general such is the case; but for the reasons considered in Sec. 118, there are many exceptions to this rule. Attempts to establish any simple relations between rainfall and runoff have not met with encouraging success.

The measurement of both rainfall and runoff is at best only approximate. The impossibilities of making an accurate estimate of rainfall have been noted. (Secs. 101 and 102.) The difficulties in the way of accurate measurements of runoff have been considered in Section 211. Even when the rainfall and runoff for the same period are determined with reasonable accuracy, the relations shown by their comparison are more or less discordant. On a large drainage area the flow passing by the gaging station at any time is the net result of all the rainfall and other conditions that have obtained on the tributaries of this area for a considerable period prior to that date. The larger the drainage area and the greater the storage above the station, the greater the lag of the stream flow in relation to the rainfall that produces it. Only on small drainage areas having relatively little storage is the effect of flooding rains realized almost immediately. On large areas the effects are not felt at distant outlets until days have elapsed, and they continue long after the rainstorm has passed. For these reasons the rainfall of one month usually affects the flow of the next month, and this becomes a large factor when the rainfall occurs late in the month. Where extensive storage obtains on a drainage area, the

effect of a rainstorm may continue for months. The selection of a water year instead of the calendar year for the study of rainfall-runoff relations is intended to obviate to some extent the lagging effects above described; but as these effects are often greatly prolonged, there is no division of the water year which will obviate the effect except perhaps under conditions when there is little rainfall for several months as in the case of some localities on the Pacific Coast, and even here some of the streams still flow at the end of the dry season, showing that the effects of the rainy season still continue. See Rainfall at San Diego and San Francisco, (Fig. 130, page 234).

222. **The Lag of Stream Flow.**—Fig. 286, page 492, shows by mass diagrams, a study of the relations of the rainfall-runoff conditions on the Wisconsin River above Necedah, Wisconsin, during 1904 and 1905. To construct such diagrams the rainfall from day to day during the year is added together as it occurs, and the accumulated sum is platted, giving an upward inclined line from January 1 to December 31. The position of the line at any date shows the amount of rain that has fallen to that date, and the slope of the line indicates its intensity and distribution. The same method is used for indicating the amount and distribution of the runoff or discharge of the stream during the year, and also the cumulative difference between the runoff and rainfall. This cumulative difference between rainfall and discharge represents evaporation, transpiration, deep seepage and, when short periods are considered, the temporary storage on the drainage area. This difference between rainfall and discharge is often termed "evaporation," but as this difference includes other losses as well, the term evaporation seems somewhat misleading and is here termed "retention" as opposed to runoff. Retention is the amount of rainfall retained either permanently or temporarily from the stream and includes seepage and storage which may or may not ultimately be delivered to the stream.

From the diagram for 1905 it will be noted that up to about March 27, a large proportion of the rainfall had not reached the stream as runoff, but about April 1, on account of increased rainfall and melting snow and ice, the rate of stream flow increased and by May 1, the discharge had reached a total of about one inch more than the total rainfall accumulated from January 1 to that date, showing that some of the rainfall of the previous calendar year, held on the area as ice or storage, had finally reached Necedah. From May 1 to 18, rainfall of about 4 inches occurred, about one inch of which was held for about 15 days before it reached Necedah, and on June 1 the runoff to date was about 1.4 inches less than the rainfall. From June 4, the retention curve in-

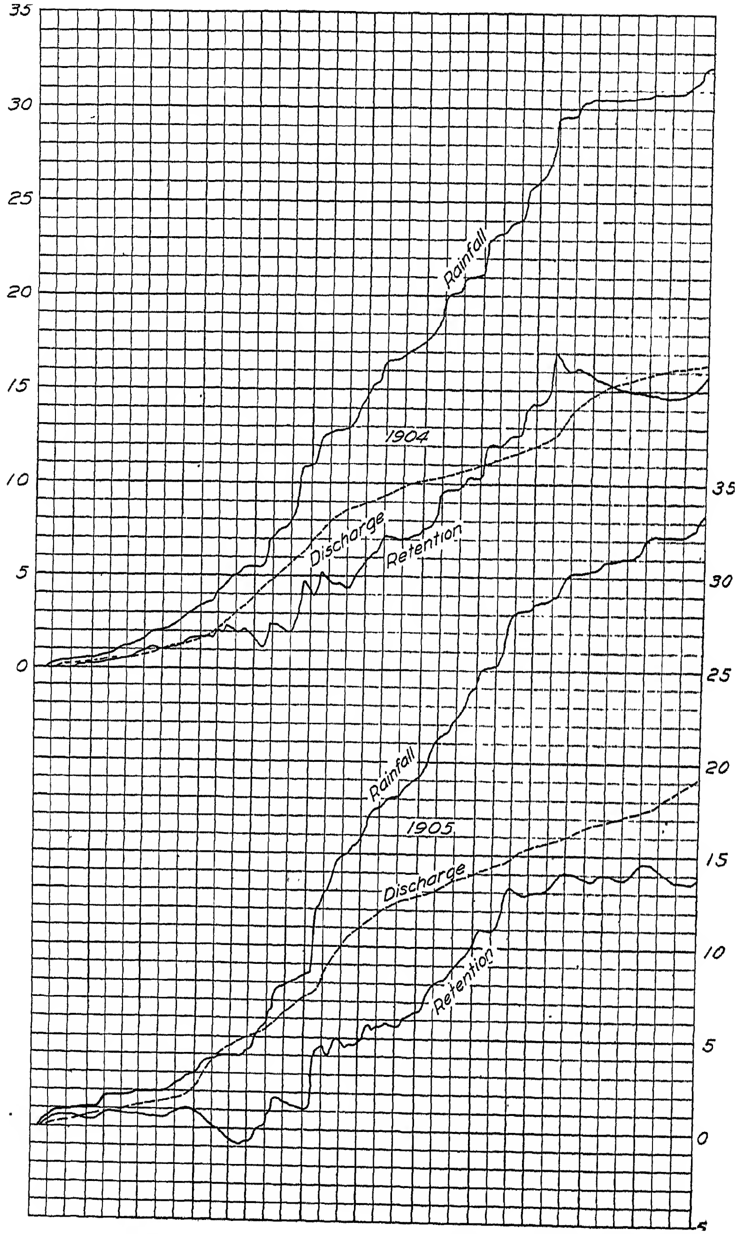

FIG. 286.—Mass Diagrams of Rainfall-Runoff Relations on the Wisconsin River above Necedah, Wisconsin.

creases much more rapidly than the discharge, as evaporation and transpiration were active. Every depression in the retention line shows a delivery to the streams of water that has been held on the drainage area, and indicates the lag relation of the rainfall to the runoff. The mass

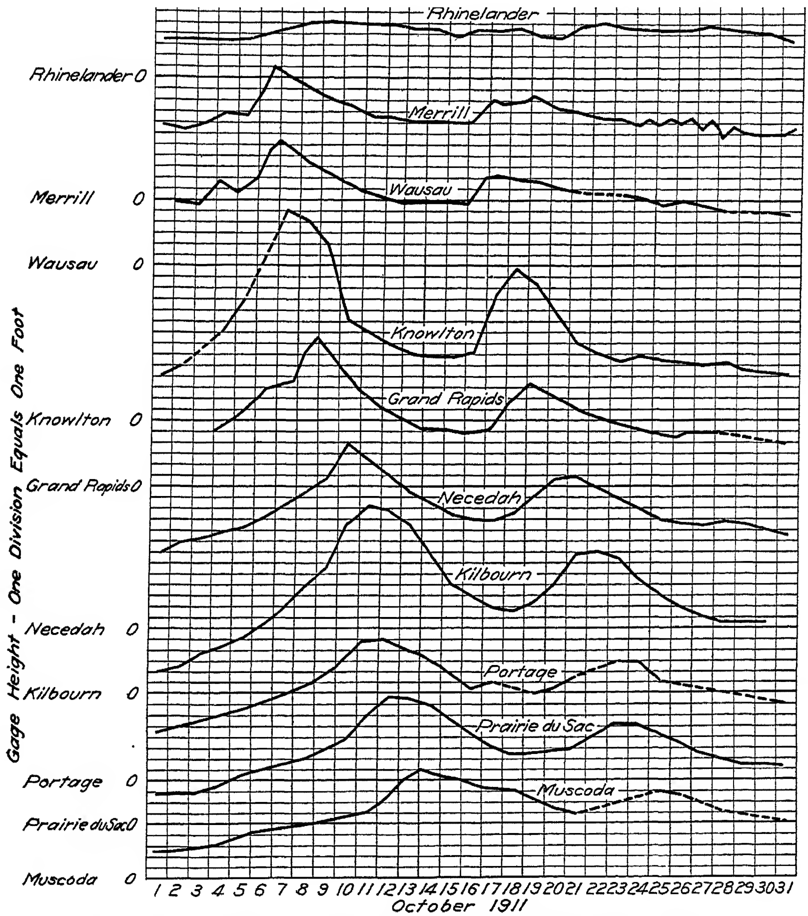

FIG. 287.—Advance of Flood Wave on the Wisconsin River.

curves for 1904, show more clearly the delivery of retained waters. From these curves it will be noted especially that the heavy rains from September 1 to October 10, 1904, did not increase the rate of flow of the stream at Necedah until about October 12, but that from October 10 to December 15, about 1½ inches that had been held in storage was delivered to the stream.

223. The Retardation of Flood Waves.—Another illustration of the lag in runoff is shown by Fig. 287, page 493, which shows the advance of a flood wave down the Wisconsin River from Rhinelander to Muscoda (Fig. 264, p. 445). This flood was caused by the storm of October 2 to 6, 1911 (Fig. 322, Sec. 246). Rhinelander is below the lakes of the Wisconsin drainage area. In this area there is considerable natural storage and also some artificial storage which has been created for power purposes. At Rhinelander there was little rise in the waters as the flood waters had been impounded, but below that point the flood wave accumulated from the lower tributaries became later and later as it proceeded down the river. At Necedah the flood wave was about four days later than at Merrill which is 151 miles farther up the river; while at Muscoda, 278 miles below Merrill, there was a lag of more than seven days. It is evident that in considering rainfall-runoff relations this lag in the effects of rainfall must be considered.

224. Effects of Storage on Runoff.—The effects of storage on runoff as shown by the mass curve of retention has been noted. Mr. C. B. Stewart[5] has determined that on some parts of the Upper Wisconsin River rainfalls of from 4 to 6 inches in the summer months will affect the stream for about five months in the approximate proportions of 65%, 19%, 10%, 4% and 2% of the total resulting runoff. Any measurements of such effects cannot be more than approximate and apply only to the individual drainage areas for which they have been determined. The method of study used by Mr. Stewart was as follows:

"Referring to the year 1907 (see Fig. 288), the ordinates to the curved lines, starting with the given average monthly runoff and drawn downward and to the right, represent approximately the rates of runoff, if no rain should occur subsequent to the month for which the respective curves, representing the underground flow was determined as follows: In September, 1907, the average monthly rainfall was 6.08″, 1.88″ above the fourteen year average. The heavy rains were distributed over a period of about a week near the middle of the month, the heavier rains at single stations being about 4.6 inches.

"The rainfall in each of the months, October, November and December, was very small, amounting to 0.87″, 0.69″ and 0.42″ respectively. The maximum daily rainfall at any one station in October and November was about 0.40″, with rains at other stations on or about the same dates averaging about 0.20″. The maximum rainfall in December at any one station was 0.30″, with rains at other stations averaging about

[5] Storage Reservoirs, by Clinton B. Stewart, Wisconsin State Board of Forestry, 1911.

0.10″. The amounts and distribution of the rainfall in these months was such that very little runoff could have resulted therefrom. Estimating the probable values for the runoff from these small rains, the

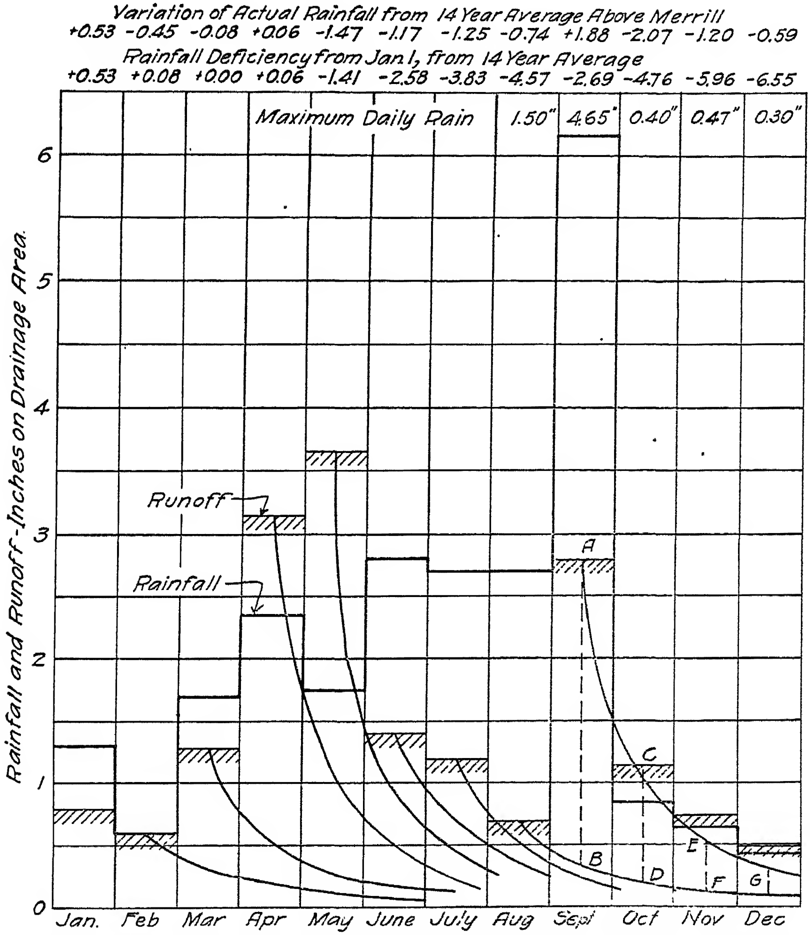

FIG. 288.—Ground Flow on the Upper Wisconsin River. After C. B. Stewart.

curve A H may be drawn. Ordinates to this curve at points A, C, E, etc., would represent with reasonable accuracy, the runoff for the corresponding months of September, October, November, etc., if no rains had occurred subsequent to September. The ordinates to the curve I H[1], similar in form to A H, at I, B, D, F, etc., would represent the runoff for the corresponding months of August, September, October, November, etc., if no rains had occurred subsequent to August."

Similar studies to those of Mr. Stewart are the basis of the ground

flow diagrams of Mr. C. C. Vermuele (Fig. 289), which he used to calculate the dry weather flow of streams from estimated depletions of the ground water. Vermuele found that the flow with full ground water in Eastern streams was in general two inches per month, and that when the depletion of the ground water occurs the monthly ground flow would vary with the average depletion for the month (Sec. 232). Curves of similar import are used by Professor Meyer as a basis for the calculation on ground flow (Sec. 234).

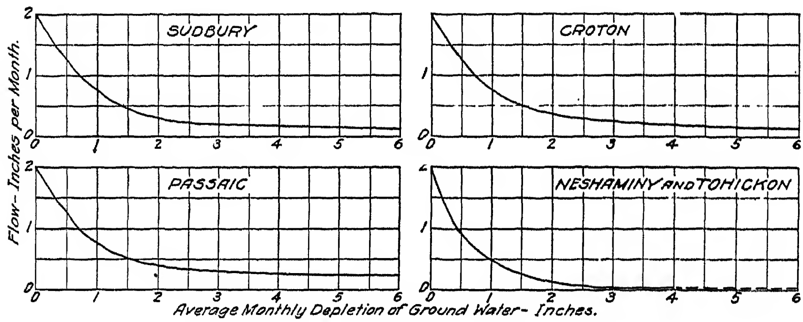

FIG. 289.—Grounds Flow Curves of Eastern Streams. After C. C. Vermuele.

225. Variation in Annual Relations of Rainfall to Runoff.—Taking into account the lag of streamflow due to surface and ground storage, it is not to be expected that any close agreement will be observed between rainfall and runoff for the same period, and the shorter the period and the larger the drainage area, the more discordant the relations which must be expected. Fig. 263, page 443, shows the relations of total annual rainfall to total annual runoff on four streams in which the data for various years are arranged in the order of the magnitude of the annual rainfall. From this diagram it will be seen that in general the annual runoff has increased with the annual rainfall but that in each case there are exceptions more or less radical. In such cases various influences have intervened and have overcome the effects on runoff due to the changes in rainfall conditions.

If a diagram be drawn (Fig. 290, p. 497) on which the annual rainfalls be represented by abscissas and the runoff by ordinates, a 45° line drawn from the zero point will represent 100% of the rainfall that might run off from a steeply inclined impervious drainage area, such as a slate roof. On account of the various losses which modify and reduce runoff, the points indicating the relations of annual rainfall to annual runoff will fall considerably below this line.

If it is assumed that retention remains fairly constant, all observa-

tions should fall upon a line drawn parallel to the 100% line and at a vertical distance therefrom equal to the average annual retention. In this case the horizontal or vertical distance between the inclined line and the 100% line represents the average annual retention, and the distance from the inclined line to the base represents the varying annual discharges. On this basis, the discharge would apparently be zero should the rainfall equal only the average retention. Where annual rainfalls decrease to this extent, it is found that some runoff usually

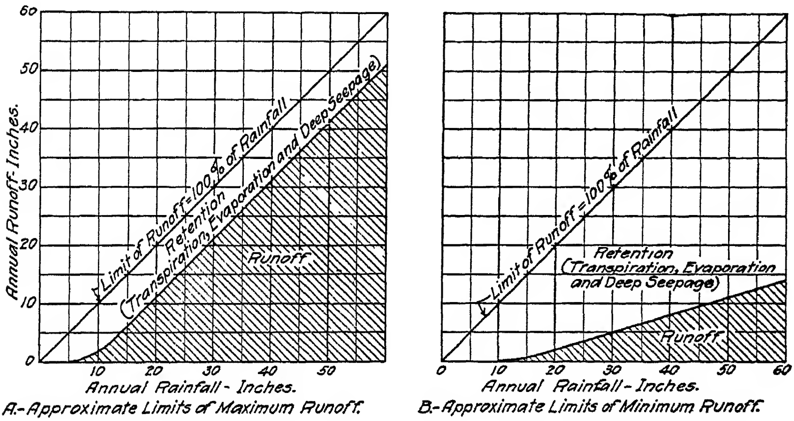

FIG. 290.—Examples of Extreme Annual Rainfall-Runoff Relations.

occurs when the rainfall is below the mean annual retention so that the general relations at these lower limits would be better represented by a curved line which becomes tangent to the base line at a point perhaps equal to about one-half the amount of the average annual retention.

Long series of observations on many streams show that in general an annual rainfall of at least five inches is necessary to produce runoff even from small drainage areas with mountainous topography, while with broad valleys and gentle slopes, no runoff will occur with an annual rainfall of less than than 10 to 15 inches. This statement is somewhat misleading as much depends upon the annual distribution and intensity of the rainfall so that the limits named are but roughly approximate. When the annual rainfall becomes more than the mean annual retention there is an increase in runoff more nearly proportional to rainfall and in general this increases with the slope of the area.

Curves drawn to represent mean annual rainfall runoff relations will begin with their zero at the limiting annual rainfall at which no runoff will occur and, in general, will run nearly parallel with the 100% line after the rain exceeds an amount perhaps double this limit. Re-

tention might be expected to increase with rainfall, for the more rainfall the greater the opportunity for loss through evaporation, transpiration and deep seepage. The consequence of increased rainfall, however, is high humidity and reduced temperatures which have a tendency to diminish these losses. In general, practical results lie between the one extreme where the normal retention remains almost constant (Fig. 290 A) and the other extreme where the annual retention increases with the annual rainfall more rapidly than the increased runoff (Fig. 290 B). In both these cases it is important to note that runoff appears as a residual after the demands of temperature, evaporation and deep seepage are supplied.

226. Approximating Rainfall-Runoff Relations.—Fig. 291 A shows the relation of annual rainfall to annual runoff of the Merrimac River above Lawrence, Massachusetts, for 36 years. The mean rainfall for this period was 41.49 inches, the mean runoff 20.06 inches, and this point is platted on the diagram in the center of gravity of the 36 years observations. The inclined lines on the diagram radiating from the left lower corner indicate the varying percentages of the rainfall appearing as runoff. The average percentage of runoff is 48.6% of the rainfall but the extreme variations are from 32.2% to 61.9%. Hence, if the discharge had been estimated on the basis of the mean percentage it would have been 51% too high in one case and 21.5% too low in the other. The line of mean annual retention is drawn parallel to the 100%. If estimates of annual flow of the Merrimac River were made on the basis of this line, the extreme variation from actual flow would be 27.5% too high in one extreme and 25.3% too low in the other extreme. The latter estimate agrees with the facts somewhat more closely than the percentage estimate but both are considerably in error, and in the consideration of the rainfall-runoff relations of many drainage areas the errors in either method would be much greater than here indicated. (Fig. 291 B.) This variation is, however, sometimes well within the limits of the factor of safety which should be allowed in such estimates.

If on these diagrams are shown not only the centers of gravity of all observations but also the center of gravity of the groups of observations both greater and less than the mean, rainfall and runoff being considered, lines to represent the mean rainfall-runoff relations with greater accuracy can be drawn through the center of gravity of the entire group and approximating the centers of gravity of the sub-groups. The angle of these lines with the base will usually be less than the 45° line of Fig. 291 A as is shown by the broken line in Fig. 291 C (after Rafter).

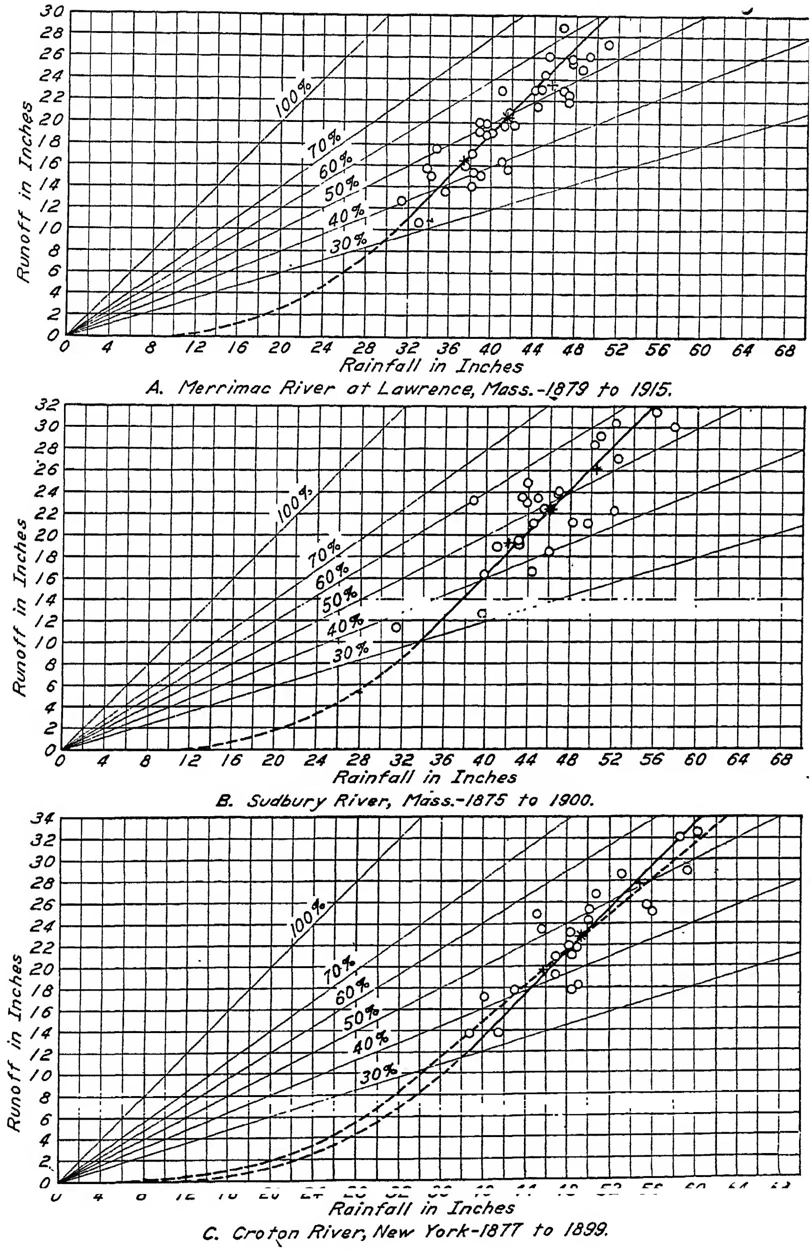

FIG. 291.—Annual Rainfall-Runoff Relation on Three Rivers of Eastern United

Diagrams to fairly represent mean annual relations must differ with various conditions on each particular drainage area and will therefore vary somewhat with every stream. C. E. Grunsky[6] has given the following rule for roughly approximating the runoff from a drainage area.

"The percentage of the annual rainfall, when less than 50 inches, which runs to the stream, is equal to the number of inches of rain. When the annual rain exceeds 50 inches, 25 inches thereof goes to the ground (evaporation); the remainder is runoff."

This statement may be useful for readily keeping in mind the general form of a mean runoff curve, but it will hardly be useful for even the rough estimates for which it was designed, except under special conditions, as will be noted by reference to Fig. 292 on which the curve representing this rule is shown (as Curve No. 4) in comparison with other curves suggested by Mr. Grunsky and others for special areas. In this figure are also platted two extreme cases of streams of high and low runoff. Curve No. 1 shows the mean annual rainfall-runoff relations on the Salt Spring Valley. This is a drainage area of 25 square miles tributary to the San Joaquin River and flowing from the west foothills of the Sierra Nevadas in Calaveras County, California. These data were corrected by Lippincott and Bennett[7] for both rainfall and runoff. This curve represents an extreme condition of high runoff. Curve No. 8 shows the mean annual rainfall-runoff relations of Boulder Creek with about 12 square miles drainage area and a mean altitude of 5500 feet above Cuyamaca Reservoir in San Diego County, California. This area represents an extreme condition of low runoff. In both cases the annual relations are also platted on the diagram to show the considerable annual departures from the mean curves. These curves and others shown on Fig. 292 are listed on the diagram, but the annual departures from the other curves are not shown as further data would lead to confusion. In examining this diagram it should be noted how widely the observations of individual years depart from the curves which represent mean annual relations and how impossible it is to use such curves as a basis for even approximately estimating the probable annual runoff from rainfall records of areas where different physical conditions obtain. Engineers of considerable experience in other matters have sometimes used such curves as a basis for water supply estimates on projects in-

[6] Rain and Runoff near San Francisco, California, by C. E. Grunsky, Trans. Am. Soc. C. E., Vol. 61, p. 514.

[7] The Relation of Rainfall to Runoff in California, by J. B. Lippincott and S. G. Bennett, Eng. News, Vol. 47, p. 467.

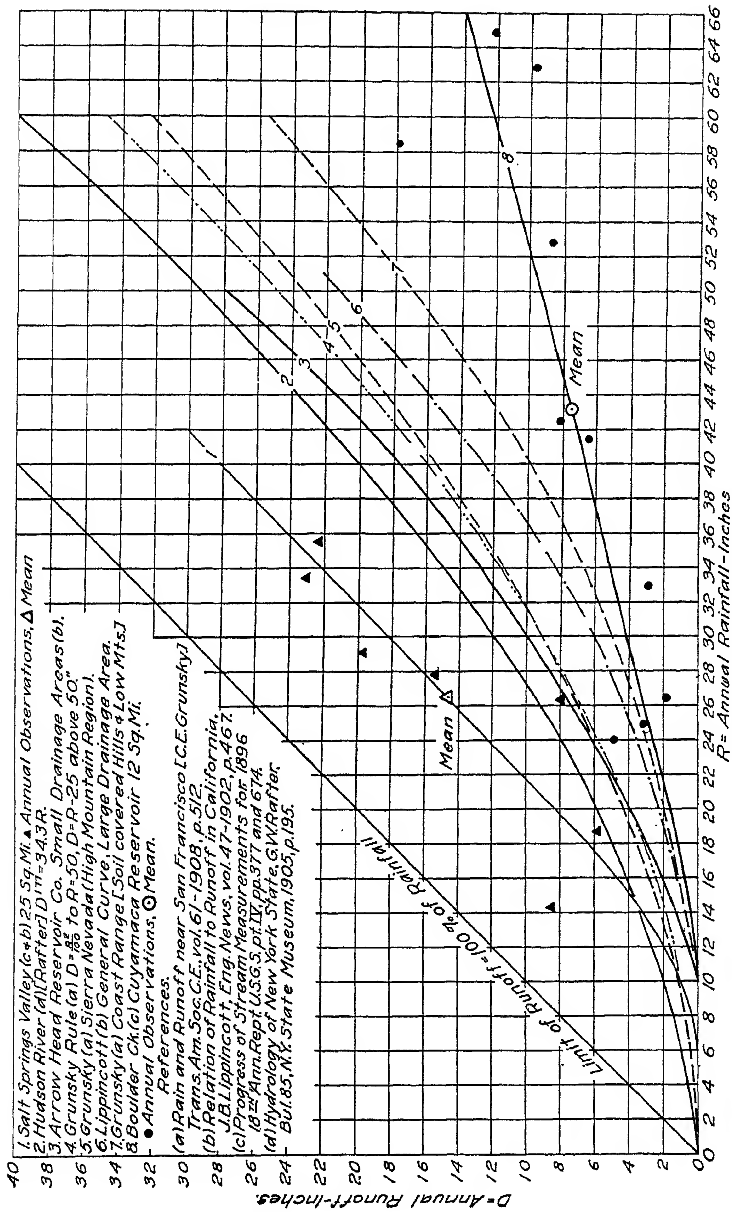

FIG. 292.—Comparison of Various Empirical Expressions for Annual Rainfall Runoff Relations.

volving large investments, although the curves are designed to show only probable mean relations for areas having certain special local characteristics. This illustration of misapplication of data should emphasize the danger of the use of either diagrams or formulas without a clear understanding of both their origin and meaning.

227. **Percentage Estimates and Empirical Expressions.**—A method of estimating runoff presented by Mr. C. C. Babb[8], involved the determination of the average annual percentage of rainfall which appears as runoff as a basis for estimating annual runoff, and the use of the average percentage of annual flow occurring monthly as a basis of estimating monthly stream flow. The previous diagrams, showing the great departure of different years from the mean annual relations (Fig. 291, page 499) and of different months from the mean monthly relations (Fig. 295, p. 506) are sufficient evidence to show the futility and danger of this method for any but the roughest approximation for runoff. The method proposed by Mr. Babb is not sufficiently accurate to indicate even the approximate means of the flows of streams that are closely adjoining but which possess characteristics different from those for which he gives data.

In Section 118 attention has been called to the fact that the division of the calendar year may not properly correspond to the division of the year best suited to the study of rainfall-runoff relations. The late George W. Rafter[9] selected a water year from December 1 to November 31 as the proper period for the study of Eastern streams and endeavored to express the annual rainfall-runoff relation by an exponential equation (No. 2 Fig. 292) which may possibly fit the varying annual relations in each particular case more accurately than any other expression.

With curves such as are shown in Figs. 291 and 292, should the actual relations correspond with the assumptions used in any particular case, the point for such year would fall directly on the assumed line, but the annual relations will usually depart somewhat from this mean relation, and the amount of the departure will indicate the effect of the distribution of rainfall and of other factors which always modify these relations. Occasionally a series of observations may agree closely with the assumptions used but in general the divergence is so marked as to render the mean relations very discordant and of little practical value as a basis for closely approximating runoff under conditions of rainfall for which no runoff observations are available. Such studies are of

[8] Rainfall and River Flow, by Cyrus C. Babb, Trans. Am. Soc. C. E., Vol. 28, page 323, 1893.

considerable importance, however, as they show in a general way the effect of the local condition on the runoff of a particular drainage area and afford a basis for the estimate of average conditions on similar areas, which is at least better than can be made without such studies. Such studies further serve to warn investigators of the marked departures from such means that will certainly obtain in every drainage area.

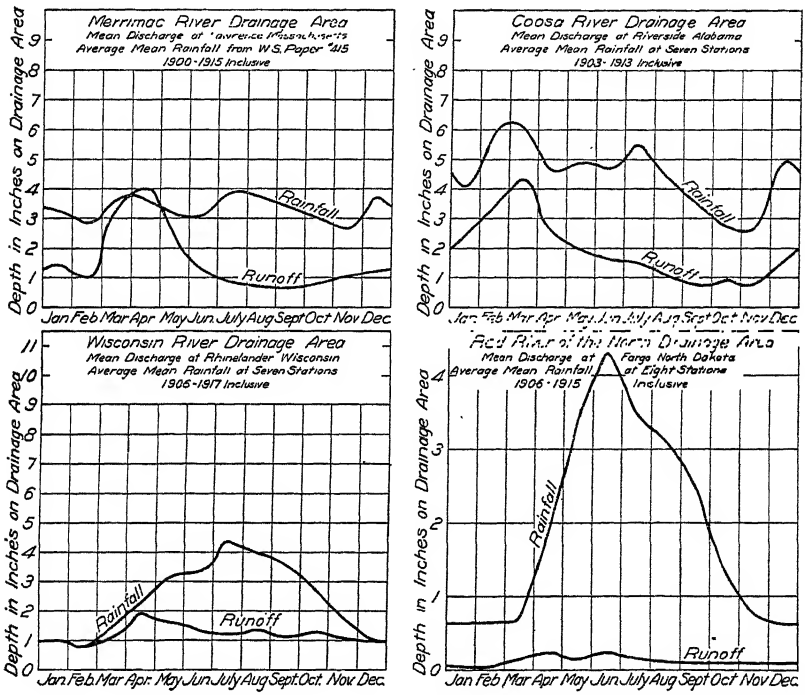

FIG. 293.—Average Distribution of Rainfall and Runoff Throughout the year for Various Streams.

228. **Variations in Periodic Rainfall and Runoff Relations.**—As would normally be expected from the previous discussion, the rainfall-runoff relations for monthly or seasonal periods are even more erratic than those for the annual period. Temperature and vegetation increase with the summer months, and a greater proportion of the rainfall is lost in evaporation and transpiration and therefore retained from the stream flow. The average seasonal rainfall-runoff relations of four streams are shown in Fig. 293. On the Merrimac River the mean maximum discharge is in April when the winter storage is delivered as runoff, and July, the month of maximum rainfall, has nearly the min-

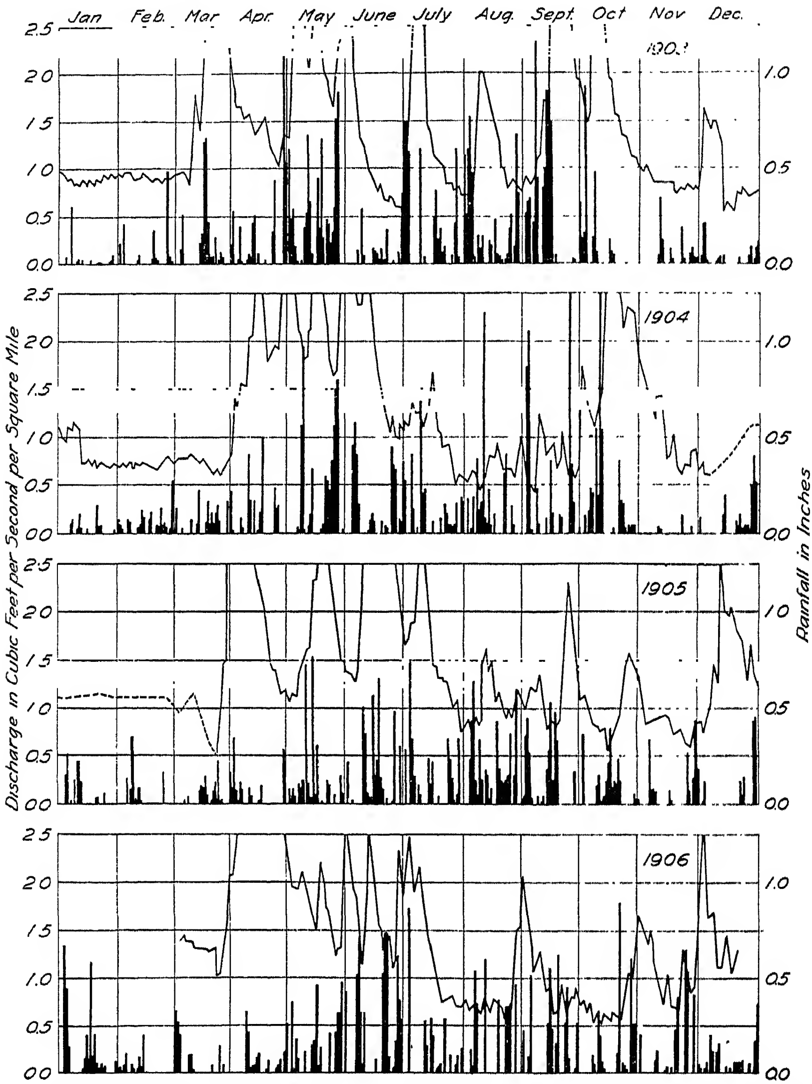

FIG. 294.—Rainfall and Stream Flow for Four Years on the Wisconsin River.

imum runoff. On the Coosa River the maximum rainfall and runoff occur in February and March, but the high rainfall of July shows comparatively little effect on the stream flow. In each case the area below the line of runoff shows the mean annual discharge while the area between the rainfall and runoff curves shows the mean annual retention.

Fig. 294, page 504, shows four annual hydrographs of the Wiscon-

sin River on which are also platted the mean daily rainfall on the area above the gaging station. The small rainfalls of March which precede the high water periods of April and May should especially be noted. The comparatively small effects of the large summer rainfalls on the flow of such periods should also be noted.

In monthly periods the lag of the streamflow and the effect of other factors in general produce very discordant relations between the rainfall and the resulting streamflow. Runoffs of more than 100% of the rainfall for the monthly periods become common in such comparisons on account of the effect of the rains of previous months. Fig. 295, page 506, is a study of these relations for monthly periods for three small streams near Philadelphia, Pennsylvania. A 45° line drawn from the lower lefthand corner of all such diagrams would indicate 100% rainfall-runoff relations, and discharges of more than 100% are found to be common for the first four months of the year. During May to August, inclusive, transpiration and evaporation are at their maximum and the proportion of runoff decreases, but even during May and August single instances are found when the runoff greatly exceeds the rainfall. This is, of course, due to heavy rains near the close of the preceding month and to low rainfalls for the month considered. For October to December, inclusive, the ratio of runoff to rainfall in general again increases on account of the reduction in evaporation and vegetable transpiration, but the relations at best are discordant and not adapted to practical use for even approximate estimates of monthly flow.

229. Rafter's Curves of Periodic Rainfall-Runoff Relations.—Rafter[9] found that monthly relations of rainfall to runoff were too discordant to be used for streamflow estimates, but divided the water year from December 1 to November 30 into the following periods:

December–May, Storage Period.
June–August, Growing Period.
September–November, Replenishing Period.

He endeavored to show that when rainfall and runoff are considered for these periods the relations may be fairly well represented by curves which may be established for each stream. Fig. 296 is a reproduction of Rafter's diagrams for the Sudbury River rainfall-runoff relations for these three periods.

On this diagram are shown the mean line of retention for the period CC, a more rational line of relation GG drawn approximately through

[9] The Relations of Rainfall to Runoff, by George W. Rafter, W. S. Paper No. 80, U. S. G. S., also Hydrology of the State of New York, by George W. Rafter, Bul. 85, N. Y. State Museum.

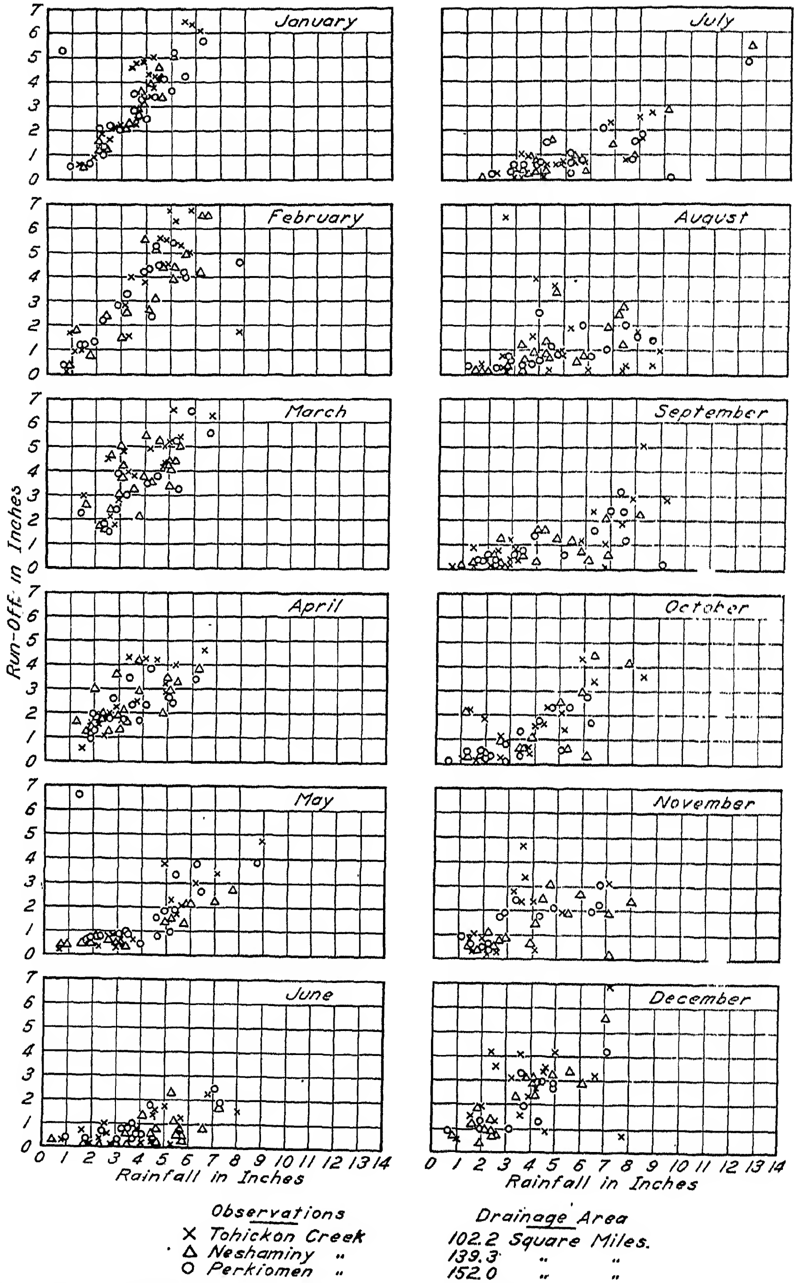

FIG. 295.—Monthly Rainfall-Runoff Relations for Three Small Streams Near Philadelphia.

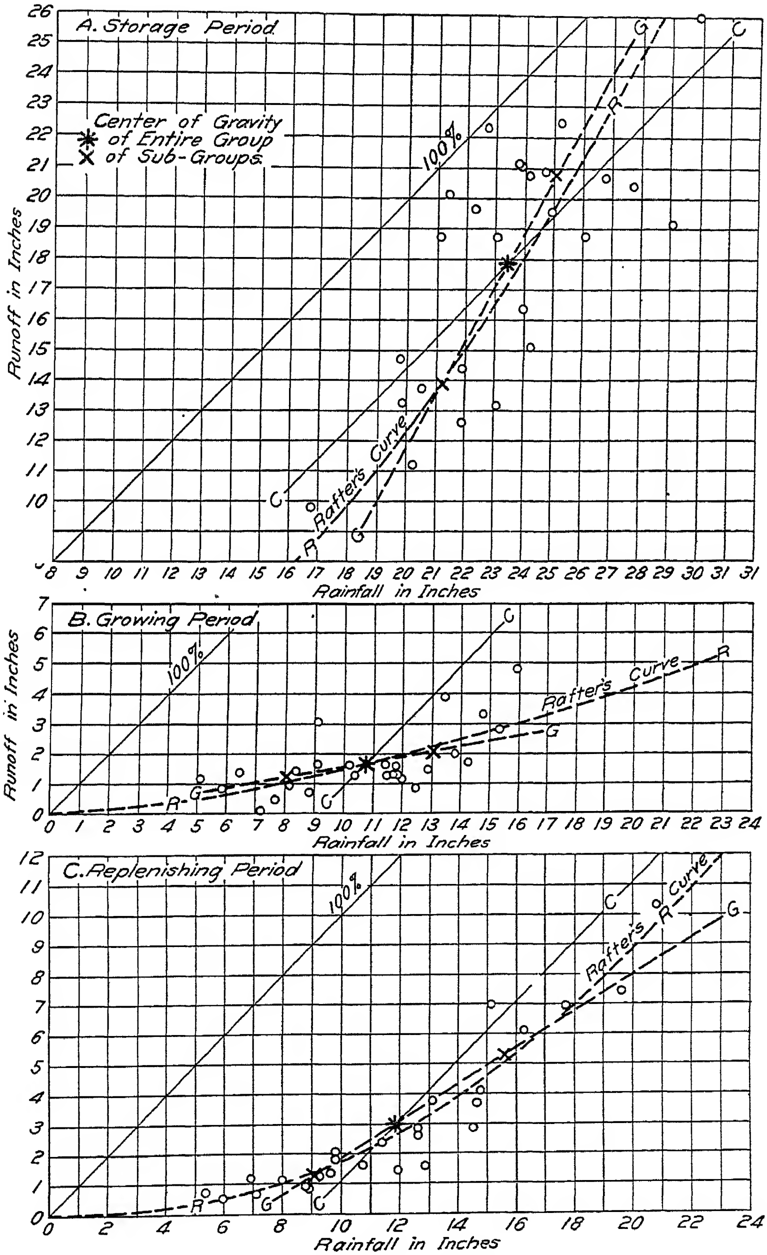

FIG. 296.—Rainfall-Runoff Relations on the Sudbury River for the periods of the Water Year. After George W. Rafter.

the center of gravity of the group, and subgroups and the curve RR drawn by Rafter as expressing his conclusions of the nearest approximation to these relations. The diagram shows, however, no closely concordant relations.

230. **Discordance in Rainfall-Runoff Relations.**—It is evident from previous discussions that there exists no simple relations between rainfall and runoff from which either monthly or annual stream discharges can be calculated with any great degree of accuracy from the known precipitation. The reasons for this are quite obvious. Runoff should be regarded as the overflow or residual remaining after various other demands are supplied and not as a proportion of rainfall. In general, the amounts of the rainfall which are retained from the runoff and are lost by evaporation, transpiration and deep seepage, are more constant in quantity than the runoff. Estimates of runoff calculated as equal to the rainfall minus a constant or increasing loss which will vary with different drainage areas, are more nearly in accord with the actual occurrences than are estimates based on fixed percentages as has been shown in Sec. 214. Such methods of expressing runoff are illustrated by Figs. 290 and 291, and are the basis of Rafter's diagrams and exponential equations. While such methods are an improvement on percentage expressions, they fail to take into account many factors which must greatly affect the flow of streams.

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CHAPTER XVIII

ESTIMATING RUNOFF

231. **Rational Methods of Estimating Runoff.**—Various methods of estimating runoff by percentage of rainfall, by experimental equations and by curves or lines drawn to fit the observed seasonal or annual rainfall-runoff relations, as nearly as practicable, have been discussed in Chapter XVII. In these cases rainfall was the only factor used as a basis for such estimates. The factors which must be considered in any rational method of computing runoff are:

1. Rainfall and its distribution throughout the year.
2. Losses from evaporation, transpiration and deep seepage.
3. Temperatures, humidities and wind velocities.
4. Topography, surface condition of soil and vegetation.
5. Storage conditions (surface and sub-surface).

To approximate the actual annual runoff conditions it clearly is necessary to take into account at least the physical conditions on the drainage area that most greatly influence runoff; and if the attempt is to be made to calculate average monthly runoff it will also be necessary to consider those conditions which cause the lag in rainfall effects discussed in Sec. 214.

In 1889 Thomas Russell[1] offered the following formulas for the runoff of the Ohio and Upper Mississippi Valleys. His formula for the Ohio River was as follows:

$$(1)\quad D = 0.600 + 0.95\,R - 0.90\,R\,(0.975\,e - 0.421\,e^2 + .066\,e^3)$$

and for the Upper Mississippi

$$(2)\quad D = 0.50 + 0.93\,R - 0.88\,R\,(1131\,e - 0.383\,e^2)$$

In these formulas

D = Runoff in cubic miles
R = Rainfall in cubic miles
e = Quantity of water necessary to saturate the air at any time

There is in these formulas a recognition of the fact that each stream is subject to a separate law and that certain atmospheric conditions will modify the rainfall-runoff relations. These formulas are found to agree but roughly with the observed stream flows.

[1] Rainfall and River Outflow in the Mississippi Valley, by Thomas Russell, Ann. Rept., Chief Signal Officer for the year 1889, Part 1, Appendix 14.

232. **Vermuele's Method.**—C. C. Vermuele[2] has derived various formulas for calculating the annual and monthly runoff of streams, based on certain relations between retention and runoff which he claims to have discovered. His general formulas for annual runoff are:

$$F = R - E \tag{1}$$

$$E = (15.50 + 0.16\,R)\ (0.05\,T - 1.48) \tag{2}$$

and for the Sudbury, Croton and Passaic Rivers

$$E = 15.50 + 0.16\,R \tag{3}$$

In which

F = Annual Runoff in inches
R = Annual Rainfall in inches
E = Annual Retention in inches
T = Mean annual temperature

Mr. Vermuele's formulas for the monthly flow of the Sudbury, Croton and Passaic Rivers are:

(e = Monthly Retention r = Monthly Rainfall)

December	$e = 0.42 + 0.10r$
January	$e = 0.27 + 0.10r$
February	$e = 0.30 + 0.10r$
March	$e = 0.48 + 0.10r$
April	$e = 0.87 + 0.10r$
May	$e = 1.87 + 0.20r$
June	$e = 2.50 + 0.25r$
July	$e = 3.00 + 0.30r$
August	$e = 2.62 + 0.25r$
September	$e = 1.63 + 0.20r$
October	$e = 0.88 + 0.12r$
November	$e = 0.66 + 0.10r$
Year	$E = 15.50 + 0.16R$

The values for monthly retention (e) for other streams are obtained by multiplying the results obtained from the formulas for each month by the factor (0.05T—1.48)

Mr. Vermuele's formulas for depletion are:

$$d_2 = d_1 + e + f - r \tag{4}$$

$$d = \frac{f}{2} + d_1 - \frac{r - e}{2} \tag{5}$$

in which

d_1 = Depletion at the end of the previous month
d_2 = Depletion at the end of the month under consideration
d = Average depletion
e = Monthly retention
r = Monthly rainfall
f = Monthly runoff

[2] Water Supply, by C. C. Vermuele, Vol. 3, Geol. Survey of New Jersey, 1894.

With all quantities in Equation 5 known by calculation or by observation except f, f can be calculated from the curves shown in Fig. 289, or from similar curves for any other streams. Later Mr. Vermuele[3] modified his formula for annual retention as follows:

$$E = (11 + 0.29\,R)\,M \qquad (6)$$

in which E and R have the same significance as in Equations 1, 2 and 3, and

M is a factor depending on the mean temperature of the atmosphere as follows:

TABLE 49

Showing Values of M Corresponding to Mean Annual Temperature

Mean Annual Temperature	Factor M	Mean Annual Temperature	Factor M
40	. 0.77	51	. 1.10
41	. 0.79	52	. 1.14
42	. 0.82	53	. 1.18
43	. 0.85	54	. 1.22
44	. 0.88	55	. 1.26
45	. 0.91	56	. 1.30
46	. 0.94	57	. 1.34
47	. 0.97	58	. 1.39
48	. 1.00	59	. 1.43
49	. 1.03	60	. 1.47
50	. 1.07	61	. 1.51

On page 149 of the report on forests[3], Mr. Vermuele compares observed and computed annual retention, and while in many of the results the agreement is quite close, some of the maximum differences shown are as follows:

TABLE 50

Table Showing Maximum Differences Between Observed and Calculated Mean Annual Retentions by Vermuele Formula

River	Observed Inches	Retention Calculated Inches	Difference Inches	Difference Percent
Potomac	24.8	28.9	—4.1	—17
Genesee	27.2	20.6	+6.6	+24
Pequest	20.5	24.0	—3.5	—17
Tohickon.............	21.3	28.2	—6.9	—32
Neshaminy	24.4	28.3	—3.9	—16
Perkiomen	24.2	28.2	—4.1	—17
Desplaines	25.0	19.8	+5.2	+21
Wande	29.3	24.5	+4.8	+17
Hemlock Lake.......	14.7	17.4	—2.7	—18

[3] Ann. Rept. State Geologist of New Jersey on Forests, 1899.

This table indicates the necessity of great care in the use of any such formulas for the calculation of even mean annual flow. The danger of attempting to adapt such formulas to seasonal flows is much greater. It is shown by Rafter (Fig. 297) that retention has no fixed relations

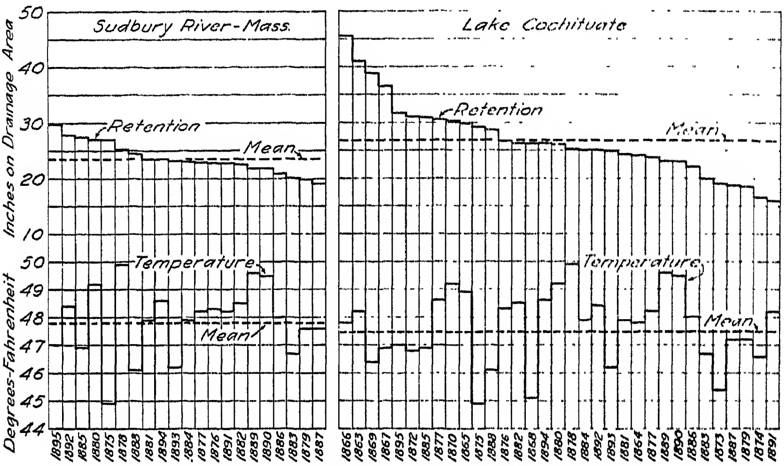


FIG. 297.—Diagrams of Retention and Temperature for Two Streams in Eastern United States. After G. W. Rafter.

to mean temperatures, at least when considered as an independent factor, and that therefore the fundamental bases of Mr. Vermuele's formula are not correct or safely applicable to general calculations of this nature.

233. **Justin's Method.**—J. D. Justin[4] has suggested an expression for annual runoff in the eastern United States as follows:

$$F = 0.934\, S^{0.155}\, \frac{R^2}{T}$$

in which

F = Annual runoff in inches
R = Annual rainfall in inches
S = Slope of drainage area found by dividing the maximum difference in elevation on the drainage area by the square root of the drainage area
T = Temperature of the drainage area in degrees Fahrenheit

Mr. Justin suggests the use of this formula to determine monthly runoffs for the calculation of data for mass curves. Such curves he regards as inaccurate as to individual months but states that such in-

[4] Derivation of Runoff from Rainfall Data, by J. D. Justin, Trans. Am. Soc. C. E., Vol. 77, p. 346.

accuracies will not affect the conclusions as to the necessary size of the reservoir for a given draft. He believes that the formula is "applicable to the Eastern United States and in general should give results within 10% of the true runoff." His tables, while agreeing more closely with the mean annual runoff of many streams, show a maximum difference in that calculated from the mean annual flow on the Passaic River of 4.6 inches or over 18 per cent. and would evidently vary still more from annual values.

Mr. Justin makes no attempt to determine the actual monthly distribution of runoff in more than a most approximate way, and the curves representing the expression cannot and do not agree with the observed annual rainfall-runoff relations any closer than the experimental equations of Rafter. He takes into account temperature and slope but neglects the ground flow conditions which make it impossible to approximate closely the seasonal variations in flow.

234. **Meyer Method.**—Professor A. F. Meyer[5] has presented a method of "computing runoff from rainfall and other physical data." In his investigations of northern states, Professor Meyer compares a rainfall year for a 12-month period beginning November 1, with a corresponding runoff year beginning on the following March 1.

This method is quite involved and depends upon such a complete knowledge of the physical conditions on the drainage area that apparently it is applicable only when more knowledge is possessed than is common in the majority of such problems. Its author has, however, applied it with considerable success to areas where no such detailed knowledge seems possible, such for example as the Ohio River above Wheeling, with 23,820 square miles of drainage area, and the Colorado River at Austin, Texas, with 37,000 square miles of drainage area.

The method is made applicable only by the acceptance of certain transpiration, evaporation, soil storage, seepage and surface flow curves which in turn depend upon a detailed knowledge of the peculiarities of flow that have taken place on the drainage area. The transpiration and evaporation curves are based on a consideration of the theoretical factors involved and of various experimental researches and were modified and revised until they gave the best results when actually applied in estimating stream flow. The curves for soil storage, surface flow and seepage flow for the calculations of the monthly runoff

[5] Computing Runoff from Rainfall and other Physical Data, by A. F. Meyer, Trans. Am. Soc. C. E., Vol. 79, p. 1056, 1915; also Hydrology, by A. F. Meyer, John Wiley and Son, 1917.

of the Root River, in which calculations Professor Meyer's methods are most completely examplified, were derived by their author "not from any group of data but on a process of logical reasoning, experience, observation, and all the facts bearing on the subject which he could command." These curves cannot be reproduced from any data or on any scientific basis. To use this method it is essential to accept these graphical empirical expressions for various constants and modify them on the lines suggested by the author and by the actual runoff relations found to exist on any drainage area to which they are applied, and this cannot safely be done except by or under the direction of an experienced hydrologist.

This method was presented as furnishing a skeleton of basic principles, and steps in the computation of runoff to which any degree of refinement may be applied to the computation by taking into account variations from the normal meteorological conditions on a given drainage area. The author states that his method should be used "principally for the purpose of analyzing, supplementing and extending observed stream flow records so as to make these records a better basis for works of improvement into which runoff enters as a factor." This method presents a distinct advance in the attempt to analyze runoff phenomena inasmuch as all of the principal factors that influence the flow of streams are considered. The disadvantage of this method lies in the necessity of accepting, temporarily at least, certain empirical variable coefficients to be taken from curves which cannot be either verified or corrected except at great labor and after many trials. Its danger lies in their acceptance without verification and their use under conditions to which they are not applicable.

235. **Basis of all Methods of Stream Flow Analysis.**—In general it will be seen that all of the methods which have been suggested or can be devised for analyzing runoff are necessarily the result of correlating observed effects (runoff) and more or less complete data of physical causes (rainfall, evaporation, transpiration, temperature, etc.). The problem is: Given a long detailed record of stream flow together with more or less detailed knowledge of physical conditions, to determine a rational method of applying the known data so that the calculated values of runoff will agree with the observed flow. The object of such methods are:

1st. To extend available observations and thus to determine the probable effects of more extreme conditions of rainfall, drought and other factors on stream flow.

2d. To enable the engineer to approximate the runoff which will obtain from any drainage area where only limited stream flow data are available.

Such studies intelligently made possess a great value in familiarizing the engineer with the influence of the various factors on the resulting stream flow, and in extending his knowledge of the stream flow which may have been experienced under extreme conditions which may have occurred but for which no records of flow are available. They are also of importance in the determination of the necessary information to be sought in the investigation of new areas, but they do not furnish a method which can be applied to the solution of such problems for new areas, and their use for such calculations by those who have not made a profound study of the entire subject, is liable to give the results of such calculations a weight to which they are not entitled.

At the present time there seems to be no rational method that can readily be applied to the accurate estimate of the seasonal distribution of runoff. In the writer's opinion, when long term records are available comparative hydrographs of adjacent streams should be used and corrected for differences in physical conditions and by at least short time observations on the stream in question. Investigations along the lines suggested by Professor Meyer should also be undertaken to confirm or correct the opinions so derived. The danger in the use of comparative hydrographs is evident for the great differences which often occur in the flow of adjacent streams have already been emphasized. Professor Meyer expresses the opinion that comparative hydrographs are of little value for supplementing stream flow data unless the characteristics of two drainage areas are identical. While this is true it is also true that calculations for any stream where runoff data are not available cannot be made with any greater degree of accuracy from the characteristics of any other stream unless it has identical characteristics which in turn cannot be determined without extended observations and actual stream flow data.

The hydrograph is a correct expression of the detailed runoff of a stream, resulting from all the varying physical conditions which have occurred on the drainage area above the gaging station previous to the time which it represents. It will express the flow of any other stream only when correctly modified for the different physical conditions which have obtained on the comparative area during the corresponding period. The effects of such differences can be only approximately determined, and the comparison is always correspondingly inexact.

236. Runoff Problems.—In estimating runoff the method employed must necessarily vary with the purposes for which the information is to be used. In general the information sought will involve the total runoff available under certain conditions of storage and distribution.

It is evident from a study of the hydrographs previously discussed that there are but few cases in which all of the runoff of a stream can be utilized to advantage under all conditions of flow. The works for the control and utilization of a stream must be built at considerable cost and their size and capacity should be limited so that the returns from the flow conserved will result in an amount adequate to meet with a safe margin, fixed charges, operating costs and maintenance. It is in general impracticable therefore to develop works of this kind so that they will be utilized to their capacity only once in a long term of years, for the cost will be too great for the benefit received.

In some cases where works are comparatively simple and inexpensive and the value of the water conserved is very great, as in the case of public water supplies for large cities, works of sufficient capacity to utilize the total flows of the lowest three to five years may be practicable. In other cases, the practicability may be limited to the total flow of the lowest year. In still other cases the flow which can be made available for the average six to eight months may be the limiting requirement; while in still other cases the flow which can be made available for the month or week of lowest flow may control.

Every case is a special problem which may vary within wide limits and must be solved in some practicable manner that will give dependable results commensurate with the risk to life, health and property involved. The problems involved may include conditions:

1st. When sufficient runoff data are available and the information sought is the amount of water which can be utilized with more or less storage.

2d. When no runoff data or only limited data are available, and when the probable runoff must be estimated by comparison with the flow of other streams or calculated from data derived from the flow of other streams.

In either case the condition may include problems:

A. Where storage is sufficient to equalize the supply over a series of dry years or at least over a series of dry months.

B. Where storage is sufficient to improve the average flow of one or two low months.

C. Where storage is sufficient to improve the flow of the days of low runoff.

D. Where storage is only sufficient to impound the low or average day's flow and make it all available during a portion of the day during which it is to be utilized.

In many problems of runoff the amount of storage available is a very important consideration. If storage is available sufficient to equalize the flow of a stream for a series of years, a knowledge of the variations in the annual runoff may be of primary importance, and the distribution of runoff during the year may be secondary. If the storage is sufficient to equalize the flow of the lowest year, or even of the one or two lowest months, then the monthly flow may be of primary importance and the distribution of flow through the month may be of little importance. In cases of limited storage, where equalization can be accomplished only for a few weeks or a few days, a knowledge of the daily distribution of flow becomes essential.

Storage then is frequently an important factor, and the problem may be to determine:

a. What storage is necessary to accomplish a certain equalization of flow; or

b. What equalization of flow can be accomplished by a certain available storage.

ESTIMATING AVAILABLE FLOW FROM KNOWN RUNOFF

237. Runoff Problems with Large Storage (Flow Known).— Rippl's graphical method of storage computation is of much value where it is desirable to utilize the average flow of a series of dry years or months by storage. This method consists in representing the net yield of a stream graphically by a mass diagram for the entire period for which observations are available or for such special dry periods as will control the extent of the project.

From a study of mass diagrams of the net available runoff may be determined:

1. The quantity of storage necessary for its utilization; or
2. The net flow that can be utilized with a known amount of storage.

To use this method of investigation the observed or estimated flow of the stream for each month is reduced by the loss due to evaporation, seepage, etc. The remainder represents the net quantity of water available. The summation of these monthly balances, added one to the other consecutively are then platted in a curve in which the abscissa of

each point represents the total time from the beginning of the period; and the ordinate, the total quantity of water available during the same interval. The scale may represent inches on the drainage area, cubic feet, acre feet, or such other unit as may be desired. Such a curve is represented in Fig. 298, by the irregular curve A-B-C-D-E-F.

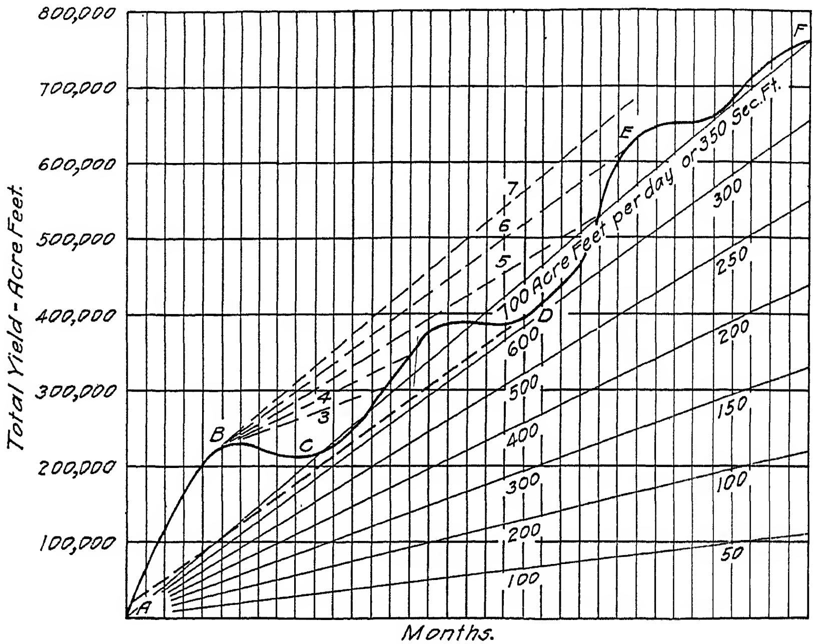


FIG. 298.—Diagram of Rippl Method of Storage Calculations.

The inclination of the curve at any point indicates the rate of the net flow at that particular time. When the curve is parallel to the horizontal axis, the flow at that time will just balance the losses caused by evaporation, seepage, etc. A negative inclination of the supply line shows that a loss from the reservoir is taking place.

In a similar manner the curve of consumption can be platted. For most purposes this can be considered a straight line as the variation in the use of water from season to season is a refinement not usually warranted, unless the uses to which it is to be put at various times of the year are well established. In Fig. 298, a series of straight lines of consumption are drawn, representing the use of water at rates of 100 to 700 acre feet per day. These rates correspond essentially to rates of from 50 to 350 cubic feet per second.

The ordinate between the supply and any demand line represents the

total surplus from the beginning of the period considered, and when the inclination of the supply line is less than that of the demand line, the yield of the drainage area is less than the demand and a reservoir is necessary.

The deficiency occurring during dry periods is found by drawing lines parallel to the demand line, or lines, and tangent to the curve at the various summits of the supply curve, as at B.

The maximum deficiency in the supply, and the necessary capacity of the reservoir to maintain the demand during the period, is shown by the maximum ordinate drawn from the tangent to the curve itself. The period during which the reservoir would be drawn below the high water line is represented by the horizontal distance between the tangent point and the first point of intersection of the curve. If the tangent from any summit parallel to any demand line fails to intersect the curve, it indicates that, during that period, the supply is inadequate for the demand. To insure a full reservoir it is necessary that a parallel tangent drawn backward from the low points on the supply curve shall intersect the curve at some point below. For example, the line B-7, representing a daily consumption of 700 acre feet, does not again intersect the curve and is therefore (within the period represented by the diagram) beyond the capacity of the stream. The line B-6 intersects the curve at E and is the limit of the stream capacity. Such a consumption will be provided by a storage of about 115,000 acre feet as represented by the length of the line 6-D, and such a reservoir will be below the flow line for about twenty-two months during the dry period illustrated in this diagram. That this reservoir will fill is shown by the intersection of the lower tangent D-A with the curve near A. The conditions necessary to maintain rates of 500, 400, and 300 second feet are shown respectively by the tangents B-5, B-4, and B-3, and the verticals 5-D, 4-C and 3-C.

If the amount of storage is known, and it is desired to ascertain the maximum demand that can be satisfied by such fixed capacity, the rate is determined by drawing various tangent lines from the summits, having the maximum ordinates equal to the fixed storage.

Mass curves showing the effects of evaporation resulting from various reservoir areas on the available flow of Tohickon Creek are shown in Fig. 89, page 153. The details of the computations on which these curves are based are given in another volume.[6]

[6] Water Power Engineering, by Daniel W. Mead, McGraw-Hill Book Co., 1915, 2d Ed., p. 179.

238. Runoff Problems with Moderate Storage (Flow Known).— When the storage available is moderate in comparison with the runoff available, a method of analysis suggested by Mr. S. B. Hill may be used to advantage. This method is illustrated by an analysis made of the probable available flow of a southern river. Fig. 299 shows the mean monthly flow of the river in question for the years 1893 to 1906 inclusive. As the higher monthly flows can not be made available the diagrams of flows above 1755 cubic feet per second are not shown. The available storage was 51,000 acre feet or 2,221,560,000 cubic feet, which is equivalent to a flow of 857 second feet for thirty days.

The maximum daily continuous flow (A. A. Fig. 299) is determined by the effect of the driest year (viz. 1904) on the storage. The effect of the dry periods on the storage is shown by the indentation into the lower or storage line of the diagram. In the year 1904 the reservoir capacity would have been just exhausted in order to maintain the maximum flows during the low months of September, October and November of that year. The amount of available continuous flow (i. e. the position of the line A-A) is determined by equalizing the deficiency in flow during the dry months with the total reservoir capacity.

It is important in the study of storage to see that in the intervening periods of excessive flow, such flows are sufficient to supply the deficiency occasioned by previous demands on the reservoir, otherwise the dry period must be considered in its relation to subsequent periods in determining the available continuous power (see Fig. 299, 1897 and 1898).

The daily flow of this river for the year 1904, is shown by the hydrograph, Fig. 301, from which it will be seen that without storage, the available flow of this stream would be limited to a minimum of 268 acre feet per day.

In order to maintain a continuous supply greater than that due to the minimum flow of the stream with storage, some source of auxiliary supply such as wells for water supply or irrigation problems, or some source of auxiliary power such as steam for power developments, must be available. If it is not desired to utilize the flow of the stream to a greater capacity than indicated in Fig. 299 or by a capacity of 1,372 acre feet per day, making the total acre feet available 1,640 (represented by line B-B, Fig. 300), an auxiliary supply or auxiliary power to the extent represented by the double cross hatched areas on this diagram, would be needed. As at all other times water would be available, the addition of steam auxiliary power apparently would be warranted to

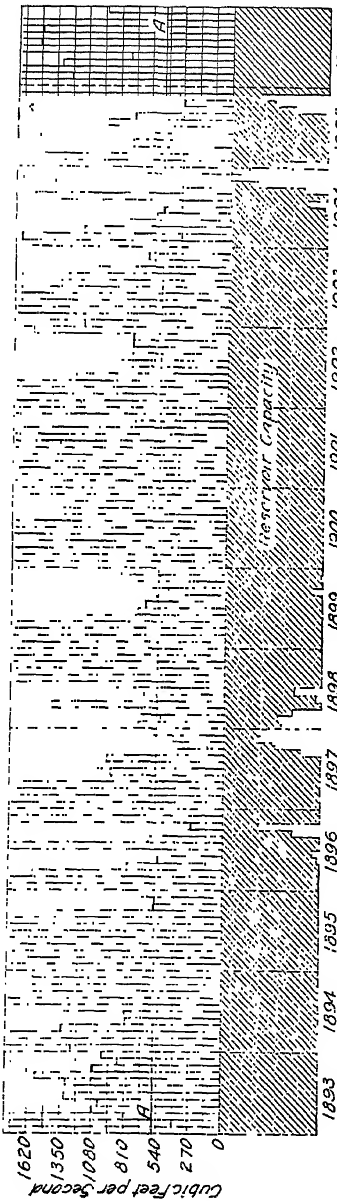


Fig. 299.—Mean Monthly Flow of a Southern River and the Effect of Certain Storage Capacity. After S. B. Hill. (See page 250.)

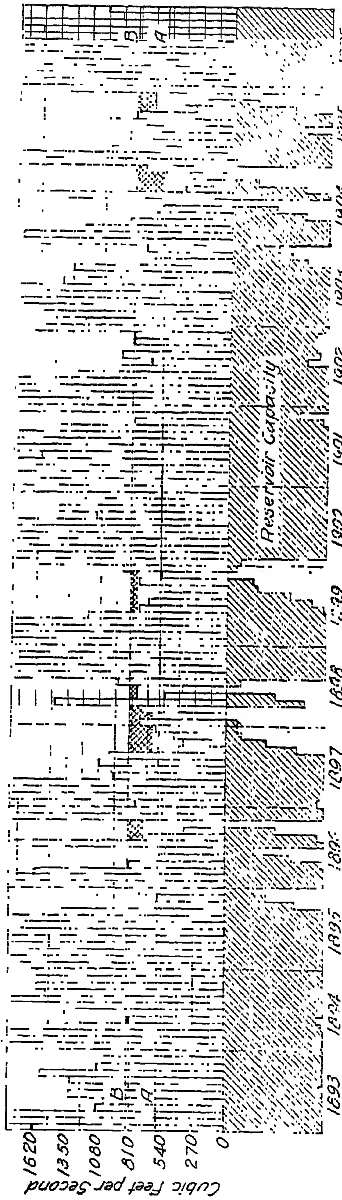


Fig. 300.—Amount of Auxiliary Power Necessary to Increase Output by 50,000 H. P. H. (See page 520.)

supply the deficiency for a power development; and if the supply is to be used for irrigation purposes, a series of wells to be pumped by auxiliary power at times of deficiency might be warranted.

239. Runoff Problems with Limited Storage (Flow Known).— In the low head water power projects and in similar supply projects for other purposes where the storage is small in relation to the total amount

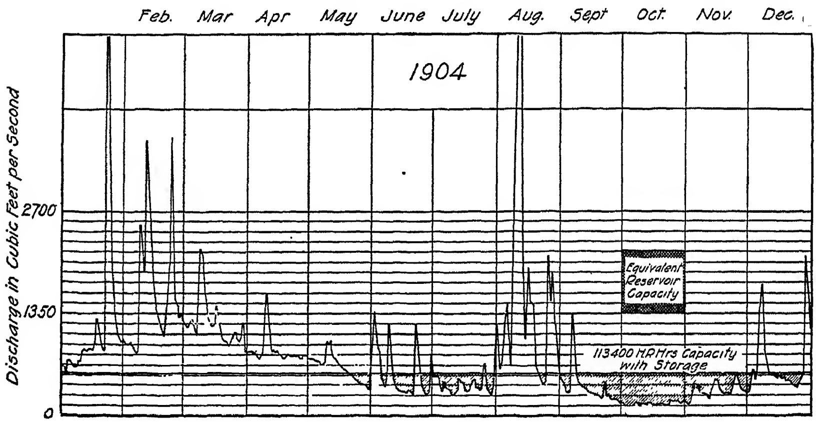


Fig. 301.—Hydrograph of a Southern River.

of streamflow, it frequently becomes desirable to analyze the probable available flow when the storage is fully utilized or to calculate the amount of storage which will be necessary to accomplish certain results.

Under these circumstances it becomes desirable to prepare hydrographs of the daily flow of the stream and to analyze the flow from month to month and from week to week in order to determine what the results would have been if such storage conditions had obtained in the past so that the future may be predicted with more or less certainty.

In 1917 such an analysis was made of the flow of the Colorado River at Austin, Texas, in order to determine the financial bearing of certain proposed betterments in the dam and power station at that place.[7] In this case almost 20 years of streamflow records were available and daily hydrographs were platted for each year. Each hydrograph included only so much of the flow as might be practically utilized in order that the scale would be sufficiently large to calculate graphically the effect of pondage and the auxiliary power needed to maintain a constant output

[7] Report on the Austin Dam, by Daniel W. Mead, City of Austin, 1917.

of 3,300 horse power. Fig. 302 shows three of these hydrographs for conditions as follows:

A. For the year of maximum runoff, 1900.

B. For a year of mean runoff, 1904.

C. For the year of minimum runoff, 1910.

The results of the investigations for these years and the means for the entire period for which data were available are shown in Table 51 and also graphically in Fig. 303.

TABLE 51

Showing Amount of Hydraulic Power which Could have been Delivered by the Austin Hydraulic Power Plant with a 60-Foot Head and the Normal Flow of the Stream; also the Amount of Auxilary Power Necessary to Maintain 3,300 Continuous Horse Power During Certain Years and for the Mean of the Period from 1898 to 1917, Inclusive.

In Thousands of Horsepower Hours

Period	1900		1904		1910		Mean 1898 to 1917	
	Hydraulic	Steam	Hydraulic	Steam	Hydraulic	Steam	Hydraulic	Steam
January	2,480	0	1,087	1,393	1,013	1,407	1,397	1,083
February	2,240	0	1,050	1,270	883	1,357	1,304	952
March	2,480	0	1,126	1,354	973	1,507	1,520	960
April	2,400	0	1,432	968	2,320	80	1,831	569
May	2,480	0	2,480	0	2,267	213	2,237	143
June	2,400	0	2,400	0	776	1,624	2,116	284
July	2,480	0	2,440	40	742	1,738	2,073	407
August	2,480	0	2,240	240	736	1,744	1,805	675
September	2,400	0	2,355	45	1,288	1,112	1,847	553
October	2,480	0	2,480	0	1,070	1,410	1,857	623
November	2,400	0	1,260	1,140	527	1,873	1,567	832
December	2,480	0	1,060	1,420	533	1,947	1,584	896
Annual	29,200	0	21,410	7,870	13,123	16,072	21,300	7,920
Percentage	100	0	67.7	32.3	44.9	55.1	72.9	27.1

While this is a special application to the study of a water power project with steam auxiliary, it is evident that the method used may also be applied to water power or water supply projects where a secondary source with comparatively large pondage may be used as an auxiliary supply.

ESTIMATING AVAILABLE FLOW FROM COMPARATIVE HYDROGRAPHS

240. Comparative Hydrographs with Large Storage (Flow Unknown).—The use of comparative hydrographs for estimating the

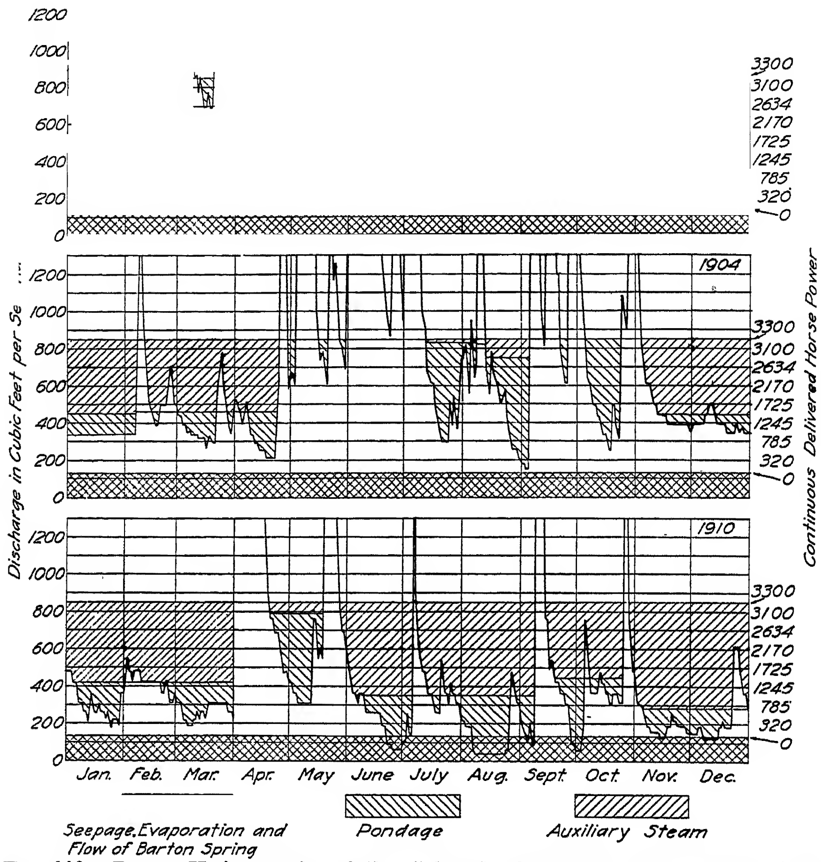


FIG. 302.—Power Hydrographs of the Colorado River at Austin, Texas (see page 523).

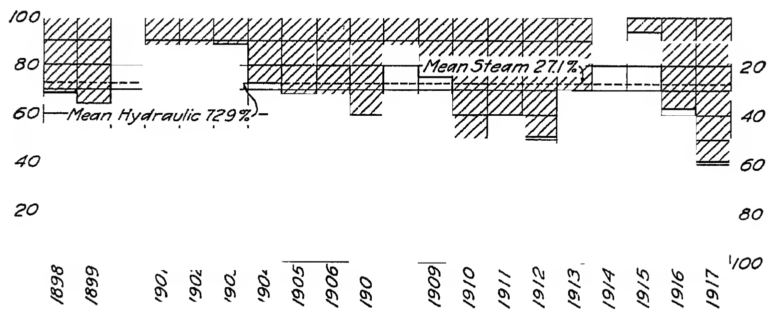


FIG. 303.—Proportion of Yearly Auxiliary Power Necessary to Maintain 3,300 Continuous Horse Power on Colorado River at Austin. (See page 523.)

flow of a stream where little or no runoff data are available is considerably simplified when large storage is practicable. During 1918 it became desirable to determine the probable amount of runoff of the Ashtabula River near Ashtabula, Ohio, that could be utilized for power purposes by the construction of certain reservoirs on the drainage area. There were no stream flow measurements available from the drainage area, hence it became necessary to estimate the probable runoff from the comparative runoff of other streams.

1. *Comparative Drainage Areas.* There were available for comparative purposes runoff measurements on nearby streams as follows:

Steam	Location	Area Sq. Miles	Data Available
Shenango River..	Sharon, Pa.	610	1-1-1910 to 1-1-1918
Cussewago Creek.	Near Meadville, Pa.	90	6-1-1910 to 1-1-1918
Shenango River..	Turnersville, Pa.	152	2-1-1912 to 1-1-1918
Shenango River..	Greenville, Pa.	107	1-1-1914 to 1-1-1918
French Creek.....	Carlton, Pa.	.....	5-1-1910 to 1-1-1918
French Creek.....	Kimmeytown, Pa.	.....	5-1-1910 to 1-1-1918

The records of the last two stations were defective as the rating curves were not well defined. The published data for French Creek at Kimmeytown indicated annual runoff almost equal to the annual rainfall, thus showing their unreliability. These two streams were also at a considerably greater distance from the Ashtabula River than the first four, so that the data from the first four streams were used in the computations.

Fig. 304 is a map of the region adjacent to Ashtabula, showing the relative location of the Ashtabula River and of the four drainage areas used as a basis for comparison, and also the location of the nearest stations where rainfall records were available, viz., at Erie, Saegerstown and Greenville, Pa., and at Warren, Hillhouse and Cleveland, Ohio.

Without considering the area of the reservoirs, the drainage area above the lower proposed reservoir dam on the Ashtabula River was 116 square miles. For safety this was estimated at 100 square miles, thus making an allowance for safety of 16% on runoff calculations.

2. *Reservoir Capacity.* In considering the development proposed, it seemed to be practicable to construct reservoirs having a total usable capacity of 1,589,500,000 cubic feet, and the estimates were made on this basis.

3. *Mass Curves of Runoff.* Mass curves of each stream (Fig. 305) showing the accumulated sum of the monthly runoffs in cubic feet per second per square mile were first platted, and the rates at which the water could be used were then determined. The rate lines are the inclined lines shown on the diagrams and begin in each mass curve at various dates when the reservoir can be considered as filled. The slope of these rate curves is determined by two requirements:

1. The capacity of the reservoir.
2. The requirement that the reservoir must be full at the close of the period.

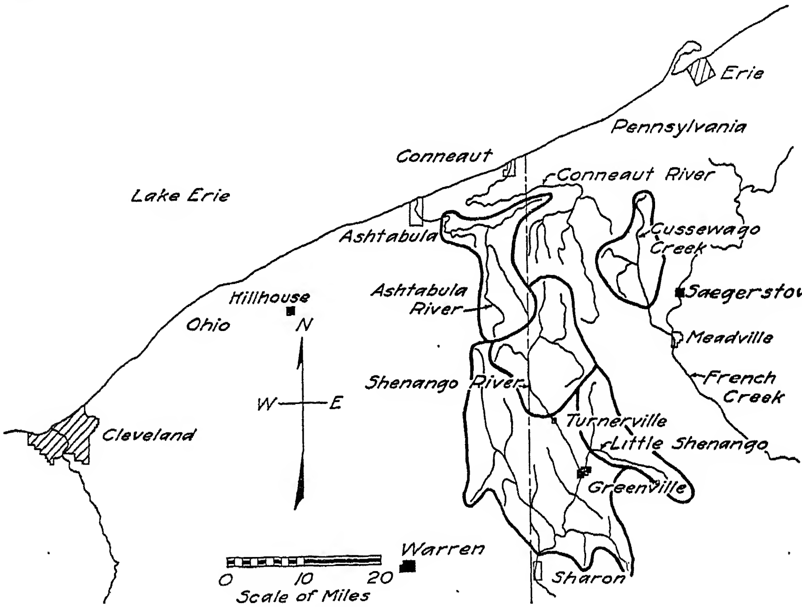


FIG. 304.—Region of the Ashtabula River and Comparative Drainage Areas. (See page 525.)

The capacity of the reservoir is indicated on the drawing by the height of the vertical lines drawn near the center of the rate lines and near the middle of the periods of deficient stream flow. The vertical lines which occasionally appear at the end of one rate line and at the beginning of another show the amount of water which would reasonably have been wasted for lack of greater reservoir capacity. The rate lines at the end of December, 1917, are drawn so as to leave the reservoirs at that date partially filled to provide for partial deficiency at the beginning of 1918, although the runoff records show that the streamflow during the

first three months will probably fill the reservoir, in addition to supplying water for a fair rate of use.

4. *Estimates of Usable runoff.*—The results of the computations for mean monthly runoff are shown on the mass curves and are summarized in the following table:

TABLE 52

Regulated Mean Annual Flow of the Ashtabula River in Cubic Feet Per Second Per Square Mile (with Storage) Based on the Actual (Regulated) Flow of Comparative Streams.

River Above	Shenango Sharon Pa.	Shenango Turnersville, Pa.	Little Shenango Greenville, Pa.	Cussewago Meadville, Pa.
Area	610 sq. mi.	152 sq. mi.	107 sq. mi.	90 sq. mi.
Year				
1910	1.26	....	....	....
1911	1.35	....	....	1.75
1912	1.62	1.58	....	1.64
1913	1.25	1.39	....	1.33
1914	1.06	1.22	1.18	1.21
1915	.99	1.24	1.33	1.19
1916	1.06	1.17	1.24	1.20
1917	1.10	1.39	1.18	1.20
Mean	1.21	1.33	1.23	1.36

Mean of all records 1.285

5. *Hydrographs.*—The hydrographs (Fig. 306) were also made on the basis of the average monthly runoff in cubic feet per second per square mile. The use, storage and waste of water is also indicated by the shaded areas. This shows in a different way how the flow could be utilized. This form of diagram if drawn to a large scale on cross section paper may also be used in calculating the available stream flow by making the water used during the dry period equal the excess runoff. This method is ordinarily less accurate and does not so clearly indicate the limiting effect of storage. The average of all the records of mean annual flow for these streams is 1.28 cubic feet per second per square mile.

6. *Geological Conditions.*—In general the drainage areas of all the streams in question are covered by drift varying from 25 to 75 feet in depth. The underlying indurated formations are not known in detail, but the entire Ashtabula River drainage area lies within the area of Devonian shales, while the other stream areas lie almost entirely within

an area of carboniferous limestones, sandstones, conglomerates and shales. Normally it would be expected therefore that the flow of the Ashtabula River would be somewhat greater than that of the other streams for the character of the underlying deposits of the four com-

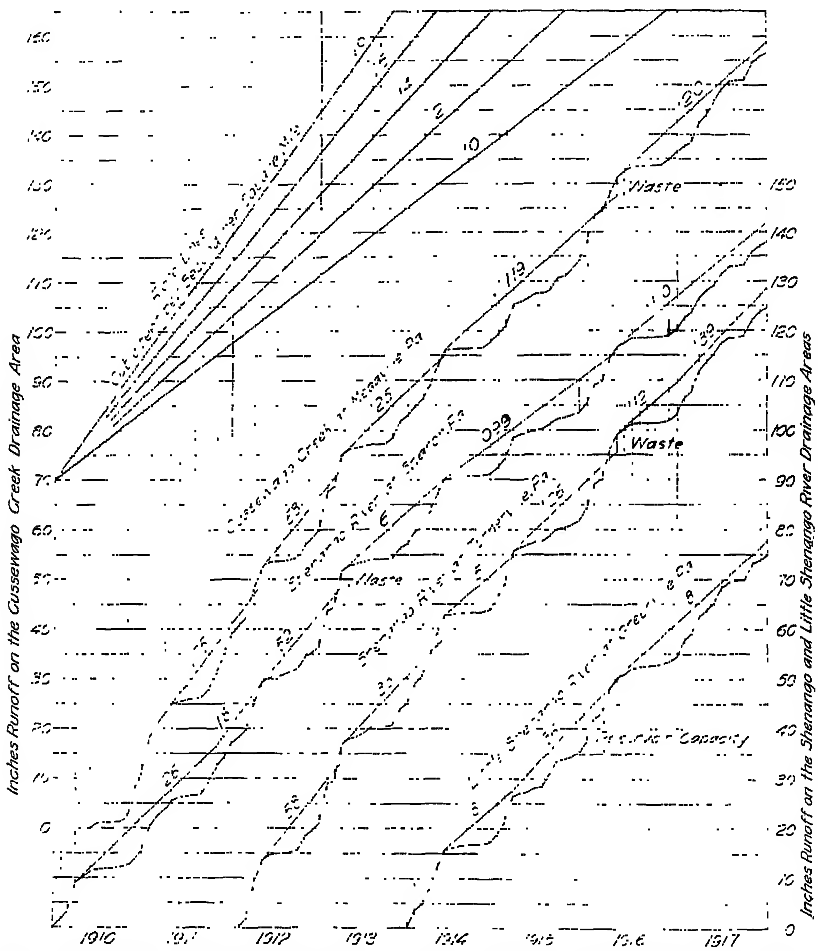


FIG. 305.—Mass Curves of Runoff of Various Streams near Ashtabula, Ohio. (See page 526.)

parative streams would probably lead to some losses from deep seepage which would not occur on the Ashtabula drainage area.

7. *Rainfall.*—To determine the distribution of the annual rainfall for the eight years for which runoff data were available, maps were drawn (Fig. 307) on which were platted isohyetal lines, for the water

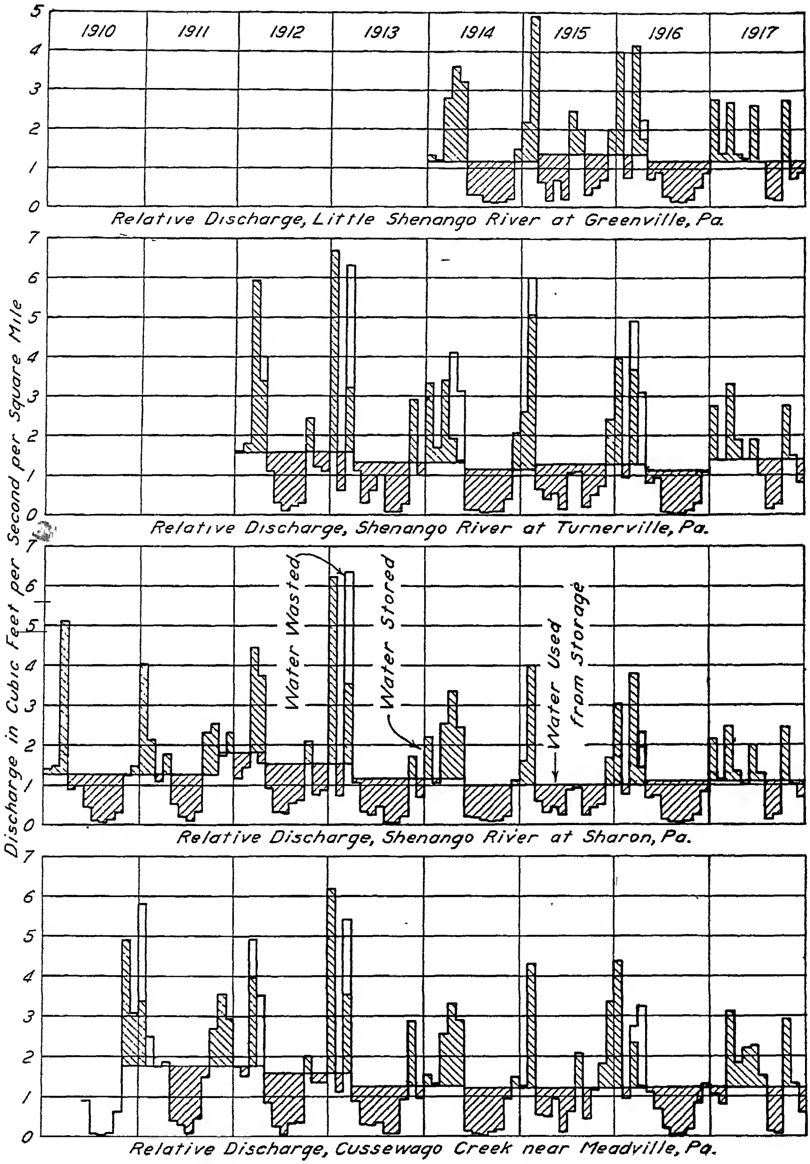


FIG. 306.—Comparative Hydrographs of Streams near Ashtabula, Ohio. (See page 527.)

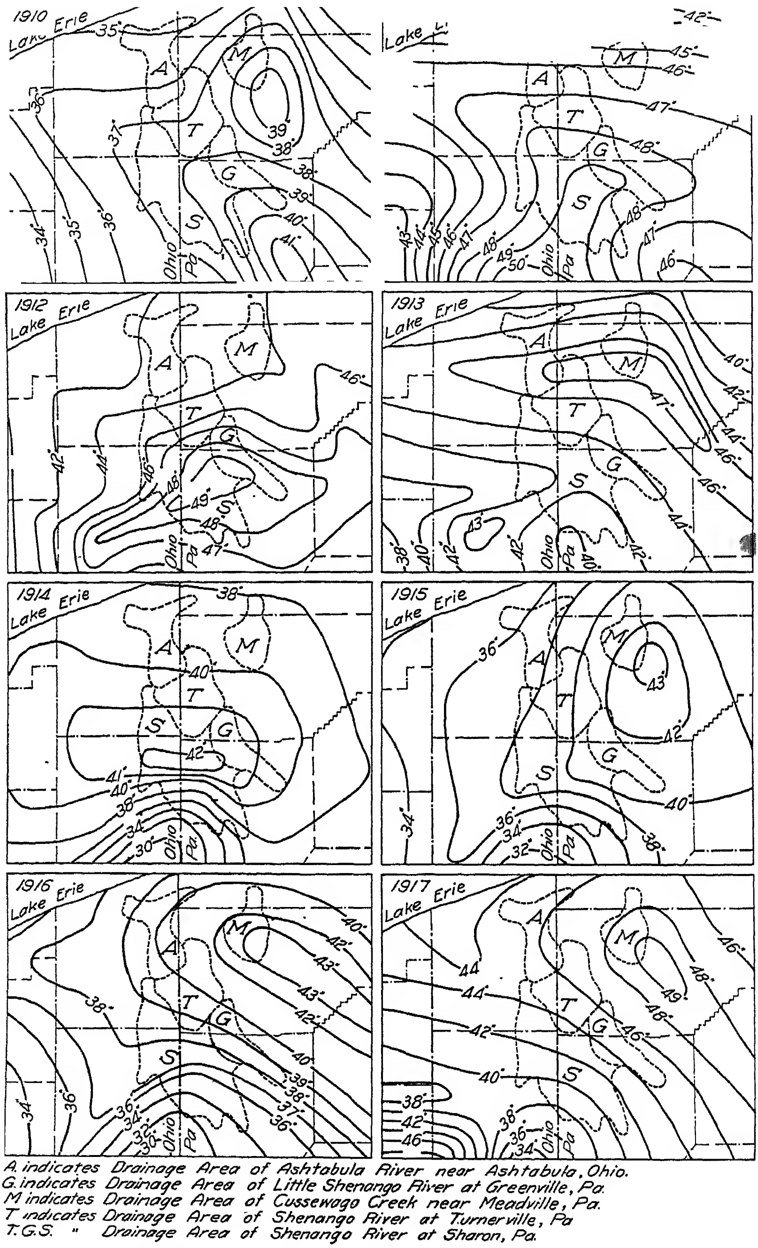


FIG. 307.—Distribution of Annual Rainfall on Drainage Areas near Ashtabula, Ohio (see page 528).

year November 1 to November 1 for each year, and from these maps the approximate annual rainfall on each drainage area was estimated. These data together with the mean annual runoff of each stream for each year of record are shown in Table 53.

TABLE 53

Annual Rainfall and Annual Runoff in Inches on Various Drainage Areas Near the Ashtabula River.

Year	Shenango Sharon		Turnersville		Little Shenango Greenville		Cussewago Meadville	
	Rain	Runoff	Rain	Runoff	Rain	Runoff	Rain	Runoff
1910	37.8	15.43	......	......	......	......	......	......
1911	48.5	21.55	......	......	......	......	45.5	27.48
1912	47.5	19.37	......	......	......	......	43.5	21.40
1913	43.8	20.68	45.5	23.99	......	......	46.5	22.88
1914	40.4	15.37	40.6	21.19	41.4	18.76	39.3	16.50
1915	40.6	13.11	39.8	18.33	41.5	18.65	42.0	19.07
1916	37.8	14.59	39.8	18.61	38.8	17.01	42.5	17.81
1917	42.6	18.03	45.5	21.69	44.5	21.18	48.4	20.37
Mean	42.10	17.37	42.24	20.74	41.55	18.65	43.96	20.79

Mean of table of annual runoff = 19.29 inches = 1.40 sec. ft. per sq. mile

A diagram (Fig. 308) was also prepared showing the mean annual rainfall for the period of record. This diagram shows that at Saegerstown, Pa., and at Hillhouse and Cleveland, Ohio, the mean annual rainfall for the seven years was less than the mean annual rainfall for the period of record, while at Erie and Greenville, Pa., and at Warren, Ohio, the mean annual rainfall for the seven years was greater than the mean annual rainfall for the period of record.

A mean annual rainfall map (Fig. 309) was also drawn from the best available long-term data to show the mean annual rainfall on all of these drainage areas. From this map it will be seen that the mean annual rainfall on the Ashtabula River drainage area has been approximately 40.5 inches. A comparison of the mean annual rainfalls shown on this map, with the mean annual rainfalls for the periods of runoff records, given in Table 53, will show that in general the long time annual rainfall means are less than the means for the periods for which runoff data are available (except on the Cussewago Creek drainage

area) ; also the mean annual rainfall on the Ashtabula drainage area is less than on the comparative drainage area.

8. *Rainfall and Runoff Relations.*—With the annual rainfall determined from these maps and the annual runoff in inches and in second feet determined from the records of runoff (Table 52, Fig. 310) were platted to determine the rainfall-runoff relations. On the four dia-

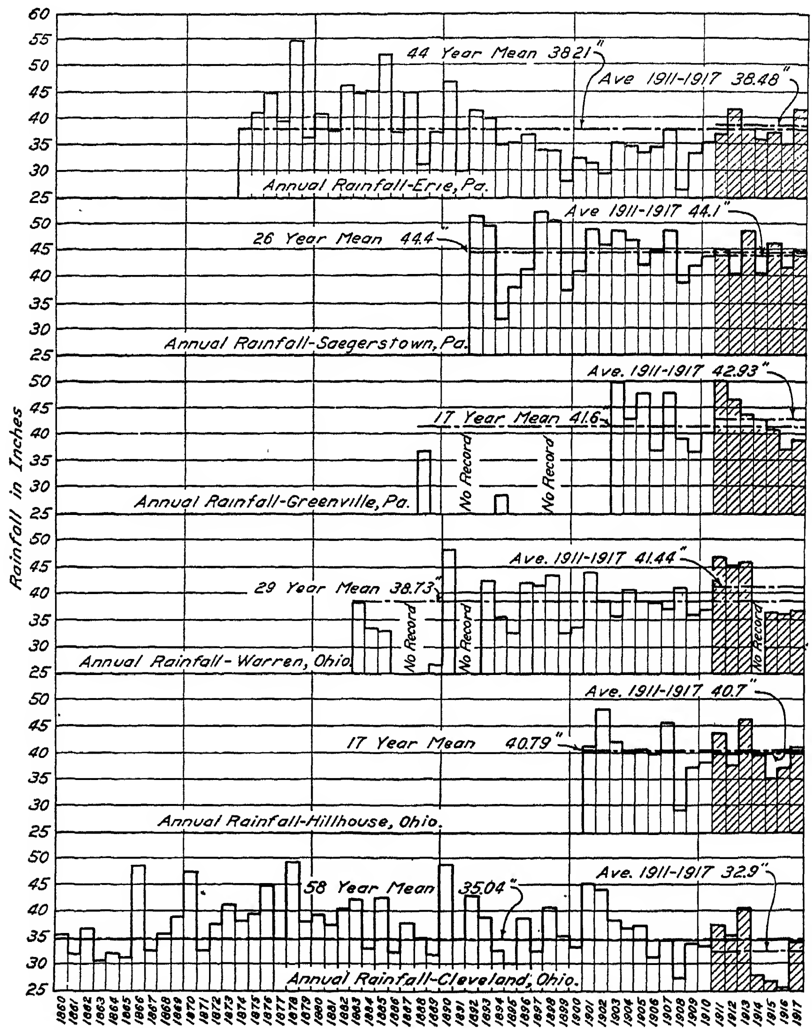


FIG. 308.—Mean Annual Rainfall at Selected Stations near Ashtabula, Ohio. (See page 531.)

grams of Fig. 310, 45° lines of mean annual retention were drawn (E, E) and also lines of mean annual rainfall-runoff relations (G, G) were drawn through the center of gravity of the entire series and for the subgroups. Lines were also drawn showing the percentage of departure + and — from the mean rainfall-runoff relations in Diagrams C and D.

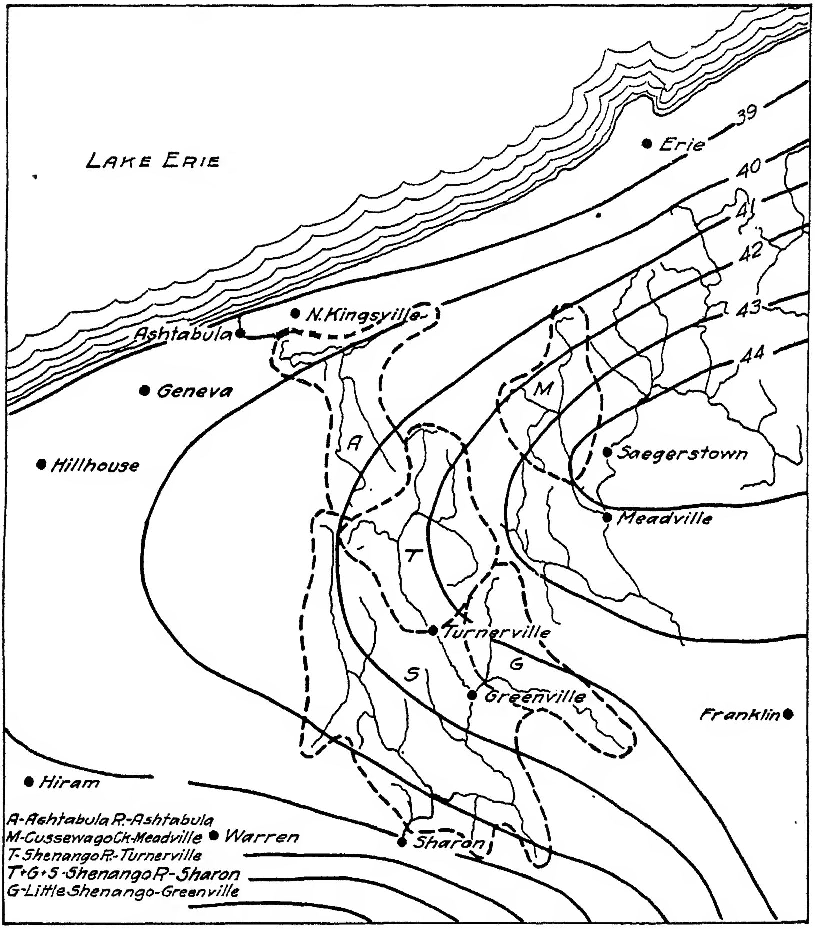


Fig. 309.—Mean Annual Rainfall on Drainage Areas near Ashtabula, Ohio. (See page 531.)

9. *Estimated Runoff on the Basis of the Mean Ashtabula Rainfall.*—On the assumption that the mean runoff on the Ashtabula drainage area would bear the same relations to the mean annual rainfall as the mean rainfall-runoff relations on the other streams, the runoff corresponding

to a mean rainfall of 40.5 inches was then determined from Fig. 310, for each drainage area as follows:

TABLE 54

Estimated Mean Annual Runoff from Various Comparative Drainage Areas Based on the Mean Annual Rainfall of the Ashtabula River Drainage Area.

	Area Sq. Miles	Rainfall Inches	Runoff	
			Inches	Second ft.
Shenango River at Sharon	610	40.5	15.9	1.15
Shenango River at Turnersville.........	152	40.5	19.6	1.42
Little Shanango at Greenville	107	40.5	18.1	1.45
Cussewago Creek at Meadville	90	40.5	16.9	1.23
Mean of four streams	....	40.5	17.6	1.28
Mean of three streams	....	....	18.2	1.37

10. *Estimated Flow of the Ashtabula River.*—It is probable that the flow of the Ashtabula River will be greater than that of the three smaller streams used for comparison. The average annual flow of these three streams is 1.37 second feet.

The larger area of the Shenango River above Sharon has the smallest relative runoff. This might normally be expected both from the size of the area and from the geology. Including this area with the others, the average annual runoff of the four streams, on the basis of an average annual rainfall of 40.5 inches, is 1.28 second feet per square mile.

It will be noted from the mass curves that the only waste of water occurs in years of high flow. The mean annual runoff for the period of runoff records is 1.40 second feet per square mile. The waste of water is shown by a comparison of the mean of Table 53 (1.40) compared with the mean of Table 52 (1.28) and is equal to 12 second feet or to 9% of the average water utilized. The average rainfall creating this waste is 42.66″ and it seems likely that for an average of 40.5″ the waste would not be more than 5%.

11. *Conclusions.*—From the data considered it would appear that the annual average flow of the Ashtabula River will probably average above 1.37 cubic feet per second per square mile of drainage area and will be at least 1.31 second feet. This should be reduced by about 9% or to 1.2 second feet for safety which, allowing 5% for probable waste,

gives a further allowance for safety of about 4%, or a total allowance for safety of at least 20% in the runoff estimates. In this case the mean available runoff was the data needed for the purpose of estimating whether the average power that could be delivered from the stream was sufficient to warrant the expense of installing a hydro electric

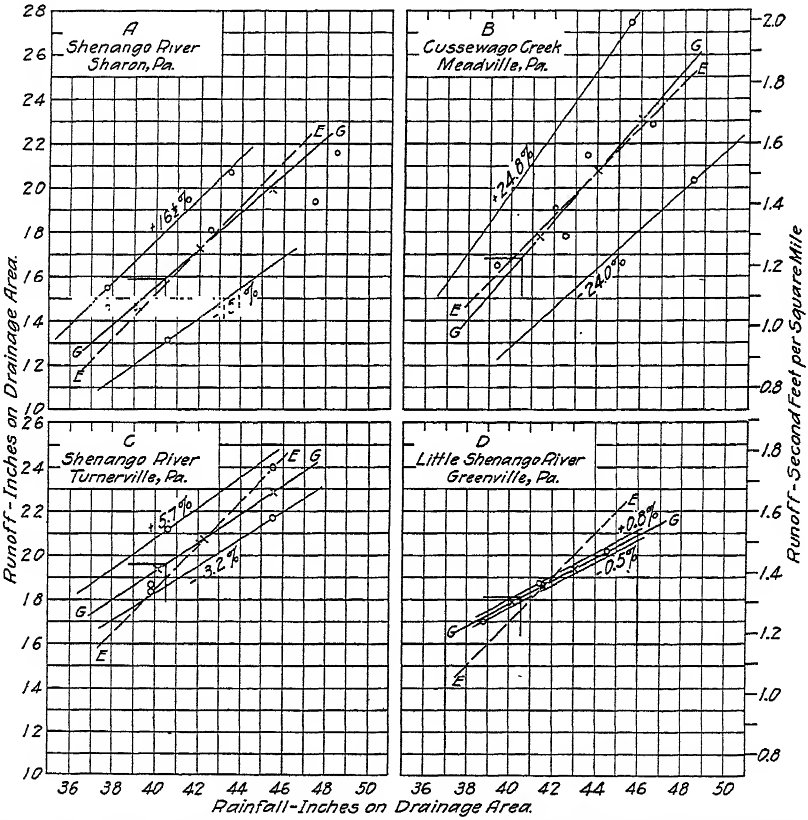


FIG. 310.—Mean Annual Rainfall-Runoff Relations for Streams near Ashtabula, Ohio. (See page 532.)

plant, which, together with the auxiliary power already installed, would maintain the total output to an economical maximum which the flow of the more productive year might warrant.

12. *Method.*—The method of estimating runoff by comparison with other streams as outlined above is evidently open to criticism as approximate and subject to considerable errors. It is believed, however, that the factor of safety used resulted in a conservative and safe estimate of runoff. This method offers a fairly definite method of proce-

dure which can be applied without radical assumptions and by engineers of limited hydrological experience. When time and expense are warranted, this method can and should be supplemented and the conclu-

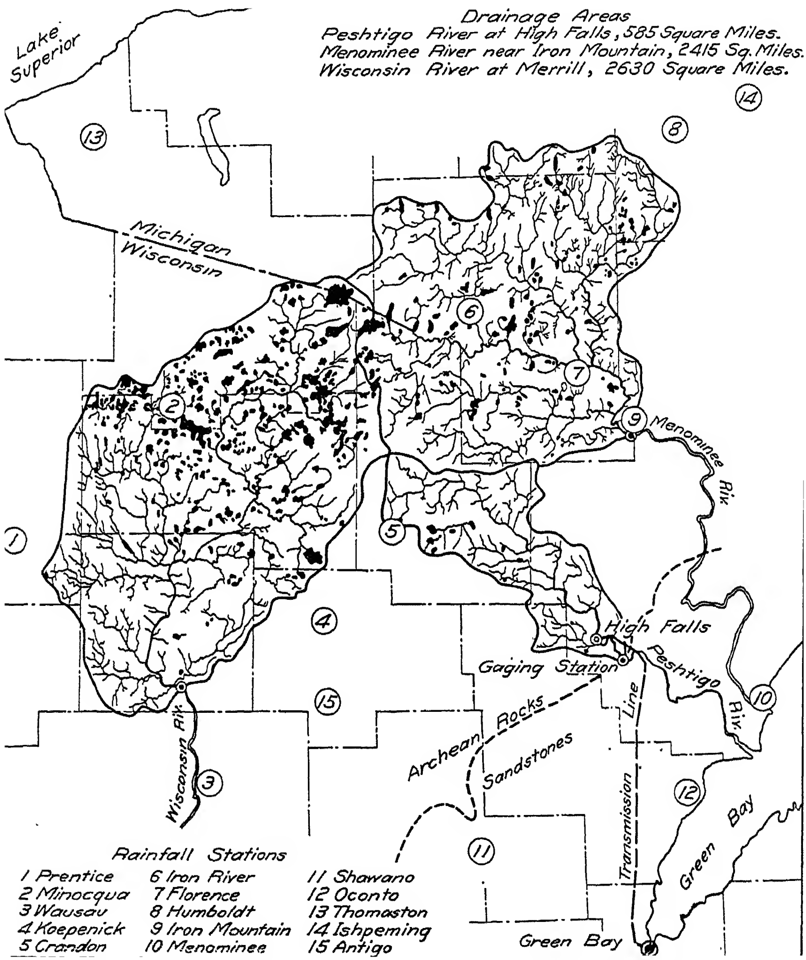
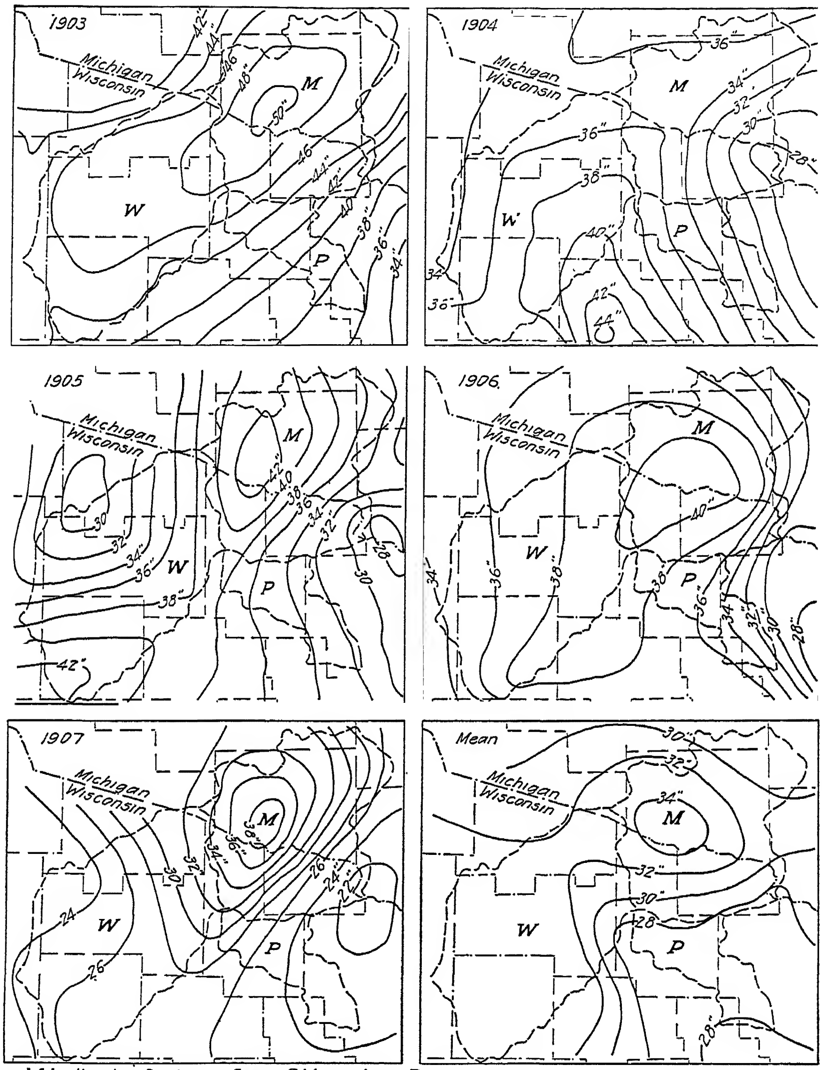


FIG. 311.—Relative Locations of Drainage Areas of the Peshtigo, Wisconsin and Menominee Rivers (see pagee 538).

sions corrected by at least short time observations of streamflow on the stream for which the estimates are made. It is also probable that a more detailed analysis of the monthly rainfall-runoff relations, somewhat on the line of the Meyer method, might serve to confirm or correct the conclusions drawn.



M indicates Drainage Area of Menominee River
P indicates Drainage Area of Peshtigo River.
W indicates Drainage Area of Wisconsin River.

FIG. 312.—Annual Rainfall on Drainage Areas of Peshtigo, Wisconsin and Menominee Drainage Areas (see page 538).

241. Estimating Available Flow with Moderate Storage from Comparative Hydrographs.—In the year 1906 investigations were begun on the feasibility of developing the Peshtigo River of Wisconsin at High Falls (see upper Frontispiece) for power purposes and con-

ducting electrical current to Green Bay to be used, with the steam electric plant already installed as auxiliary, for the purpose of furnishing power and light to that City. Surveys were made from Johnsons Falls (about 3¼ miles below High Falls) to Cauldron Falls (about 7½ miles above High Falls) and as the project looked favorable, a gaging station was established near a farm house 9 miles below the dam site. In 1908 the question of construction became important and estimates of the probable flow of the stream became necessary. At the time this estimate had to be made there were one year's gagings available on the Peshtigo River and about five years' gagings on the Wisconsin River at Merrill, and on the Menominee River near Iron Mountain, Michigan.

1. *Physical Conditions.* The relative locations of the drainage areas of these streams are shown on the map (Fig. 311). All of the areas considered lie within the boundaries of the kettle moraine of the second glacial period and within the geological limits of the Archean and Algonquin Rocks. The Wisconsin drainage area has the greatest amount of surface storage in lakes and swamps and considerable deposits of sandy soils of the second glacial epoch are found on all three drainage areas.

2. *Rainfall.*—The distribution of the annual rainfall for the water year beginning Dec. 1 and for the five years for which runoff records were available and the mean annual rainfall for the years preceding 1908, are shown on the series of maps in Fig. 312. From these maps the mean annual rainfalls on each drainage area for each year, for the mean of the five years of runoff records and for the mean of the period of rainfall records were determined and are shown in Table 55.

TABLE 55

Mean Annual Rainfalls on Peshtigo River and Comparative Drainage Areas.

Drainage Areas	1903	1904	1905	1906	1907	5-Year Mean	Mean Annual Rainfall
Peshtigo	42.1	34	34.5	36	24.5	34.2	27.2
Wisconsin	46.5	36	36	38	27.5	37.3	33
Menominee	46.5	39.5	39.5	39	32	38.2	32

The average annual rainfalls at certain stations adjacent to the three drainage areas considered are shown in Fig. 313, page 539.

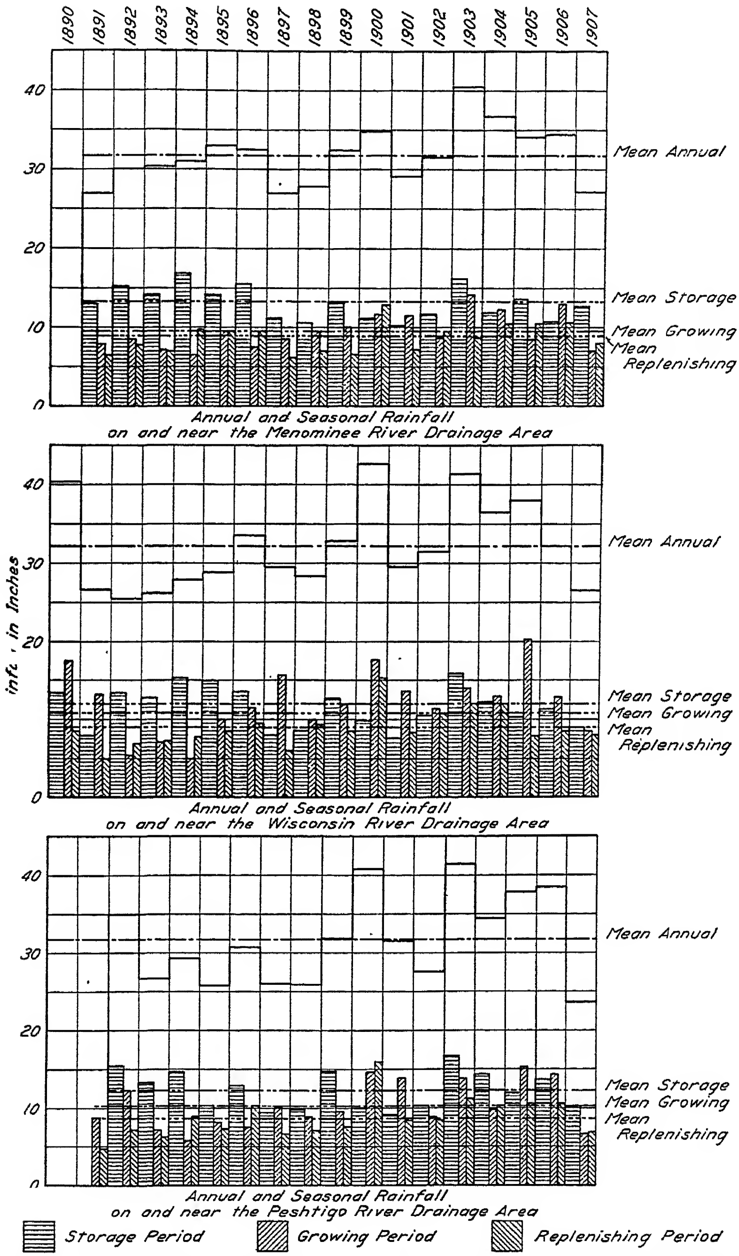


FIG. 313.—Annual Rainfall at Stations on the Peshtigo, Wisconsin and Menominee Drainage Areas (see page 538).

3. *Runoff.*—A comparison of the hydrographs of the Peshtigo, Wisconsin and Menominee Rivers, showing the discharge in cubic feet per second per square mile for the year 1907, is shown in Fig. 283, page 487.

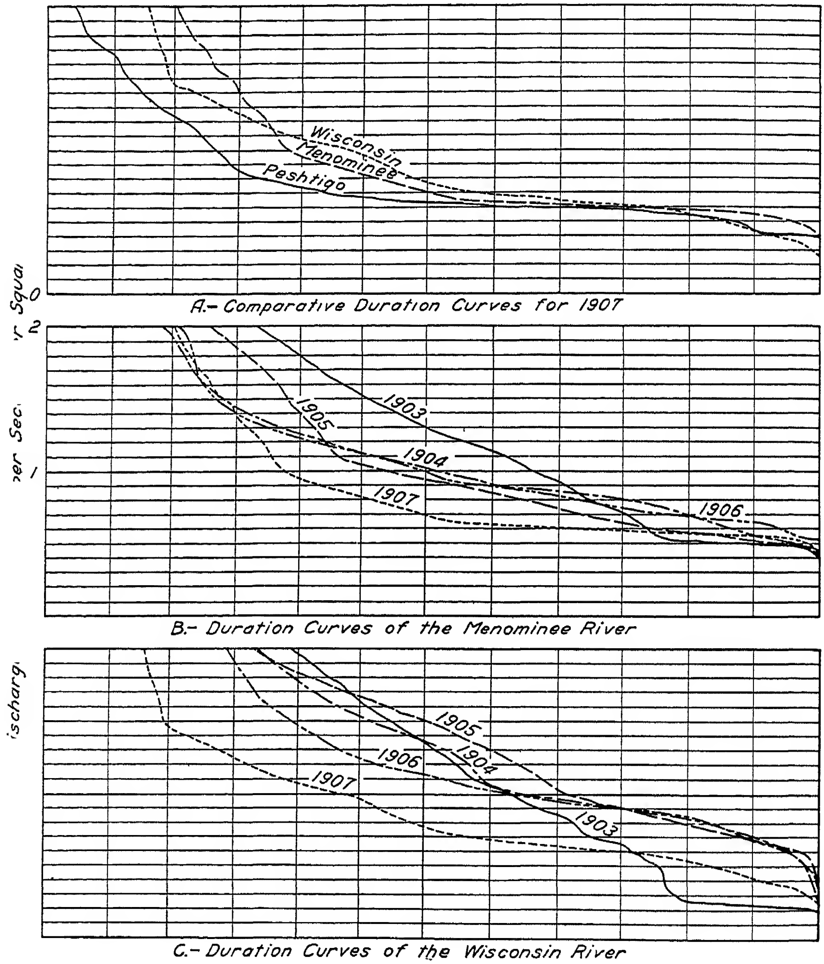


Fig. 314.—Duration Curves of the Peshtigo, Wisconsin and Menominee Rivers.

From these hydrographs, corrected for flow under ice conditions, the comparative duration curves for these three rivers and for the year 1907 were made (Fig. 314–A). These duration curves show the same data as shown by the hydrographs (Fig. 283) except that the daily runoffs are shown arranged in the order of their magnitude. With

the storage available above High Falls, these curves would all be maintained to a minimum of .645 cubic feet per second per square mile. As the annual rainfall on the Peshtigo drainage area for the year 1907 was a minimum for the 16 years of annual rainfall records, and about 10% below the mean annual rainfall on the drainage area, it seemed probable that the flow of that stream for that year reaches a minimum that would rarely be reached. It should also be noted that although the annual rainfall for 1907 on the Peshtigo River was 10% less than on the Wisconsin and 23% less than on the Menominee, the low water flow for the lowest six months of the year was well maintained and only slightly less than that of the two comparative streams.

Comparative hydrographs of both the Wisconsin and Menominee Rivers were also made and studied. The daily hydrographs for the Menominee River are shown in Fig. 315. Duration curves for both streams for the five years of records are shown in Figs. 314. The rainfall diagrams of Fig. 313, and the Table 55, both show that the annual rainfalls for 1903, 1904, 1905 and 1906 on both the Wisconsin and the Menominee drainage areas were considerably above the mean annual rainfall for the period of rainfall records, but that the annual rainfall for 1907 on both areas was much less than the mean and very near the minimum for the period of record.

4. *Conclusions.*—It was concluded from this study that the average flow would probably be at least 10% greater than shown by the 1907 hydrograph and duration curves; that there might be years of somewhat less flow which could be cared for by the Green Bay steam plant; that the hydrograph and duration curve of the Peshtigo River for the year 1907 furnished a conservative basis for estimating the average annual available water supply; and that if such as an average would furnish an amount of power which would be profitable when the cost of installation and operation was considered, then the project was feasible. The final conclusions were that a dependable average flow of 377 second feet was available which with the 85 foot head, which could be developed, would at 80% efficiency produce at the turbine shaft 70,000 horse power hours per day, and that with the steam auxiliary power available at Green Bay it would pay to develop the hydraulic plant to to a capacity of 485 second feet or 90,000 horse power hours per day.

It may also be noted that the plant at High Falls was duly constructed (see Frontispiece, lower figure) and has been operated successfully and profitably. A hydrograph showing the natural stream flow, the water used and the water wasted, as well as the variations in head in the reservoir for the year 1917, is shown in Fig. 278, page 475.

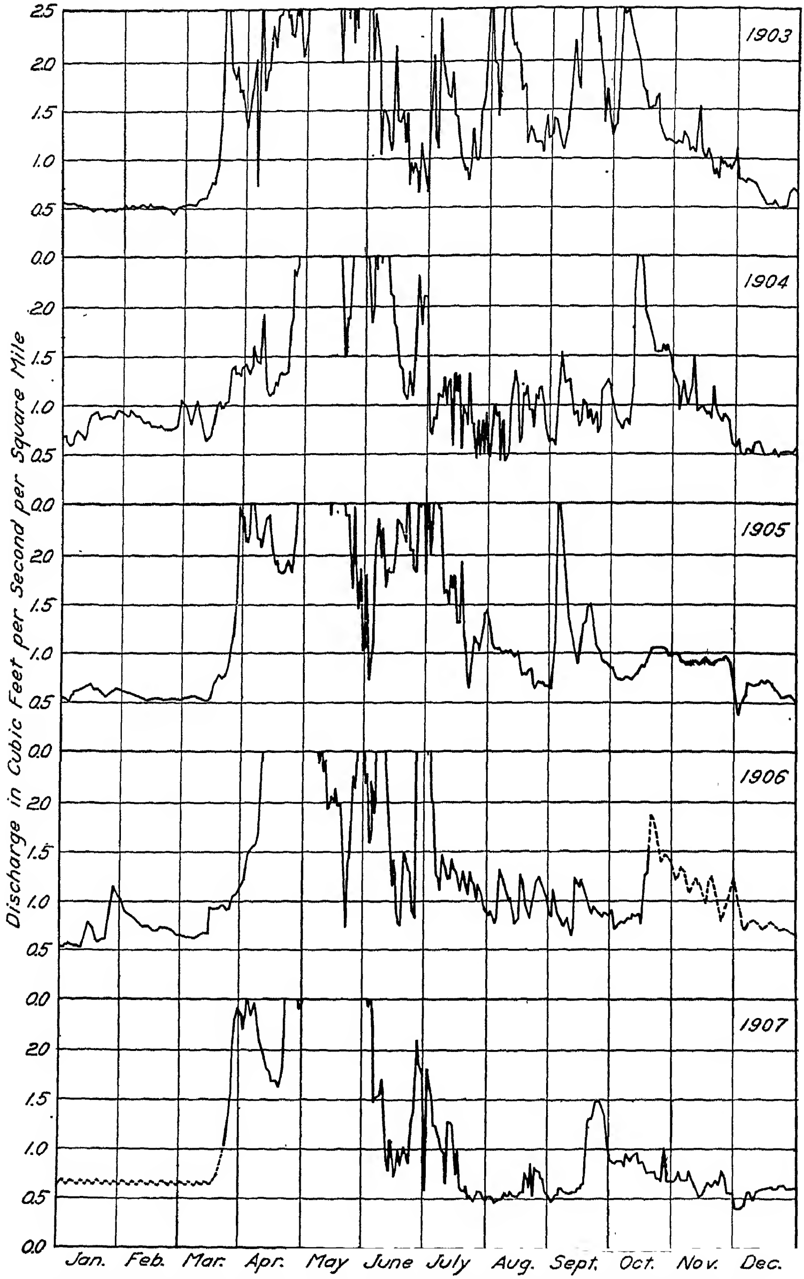


FIG. 315.—Hydrographs of the Menominee River (see page 541).

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CHAPTER XIX

FLOODS AND FLOOD FLOWS

242. **The Importance of Flood Studies.**—The problems of flood relief with which the engineer has most commonly to deal are the protection of populous districts of cities by the construction of storm water sewers, and the drainage of agricultural lands by canals and ditches. Closely connected with such works are the design and construction of channel improvements and levees for the protection of city and agricultural areas from the flood overflow of creeks and rivers bordering on or passing through areas to be protected or improved. Still greater problems arise when important communities must be protected from the damages occasioned by great floods where conditions must be improved by still more comprehensive works, including river diversion and training works, channel improvements, levees and revetments and perhaps the construction of impounding and retarding reservoirs.

The railroad engineer finds constant need for the study of flood conditions in order to design the culverts and bridges frequently necessary along the railroad rights of way, with sufficient capacity and stability to protect tracks and embankments from washouts and the attendant results. In water supply, water power and irrigation work the engineer must often design structures to impound, conserve and utilize water supplies, and must provide suitable spillways, wasteways and flood gates to pass the occasional high flood flows in order to protect such structures and the lives and property of the communities lying in the valleys below. Such works are rapidly increasing in number and importance with the growth and development of the country, and the consequences of ignoring flood conditions, of understimating flood intensities or of improper designs to meet the contingencies of floods are constantly becoming more serious and involving almost yearly great losses in property and occasionally large losses in life.

243. **Changing Conditions and Flood Effects.**—In general the flood plains of streams have been created by the streams themselves and channels have been maintained only commensurate with the normal floods which annually flow through the channels. The occasional high flood overflows the river banks, the extreme flood which occurs only at rare intervals may find the channel entirely insufficient (Table 56) and overflow the entire flood plains from hill to hill. (Fig. 316.) In the

TABLE 56.

Present Channel Capacities in the Cities of the Miami Valley Compared with the 1913 Flood Discharge.[1]

City	Channel Capacity Sec. Feet	Flood Discharge Sec. Feet	Ratio Per Cent	Drainage Area Sq. Miles
Sidney	10,000	44,000	22.7	555
Piqua	25,000	70,000	35.7	842
Troy	20,000	90,000	22.2	908
Dayton	90,000	250,000	36.0	2,525
Dayton (Below Wolf Creek)	100,000	252,000	39.7	2,598
Miamisburg	65,000	257,000	25.3	2,722
Franklin	65,000	267,000	24.3	2,785
Middletown	115,000	304,000	37.8	3,162
Hamilton	100,000	352,000	28.4	3,672

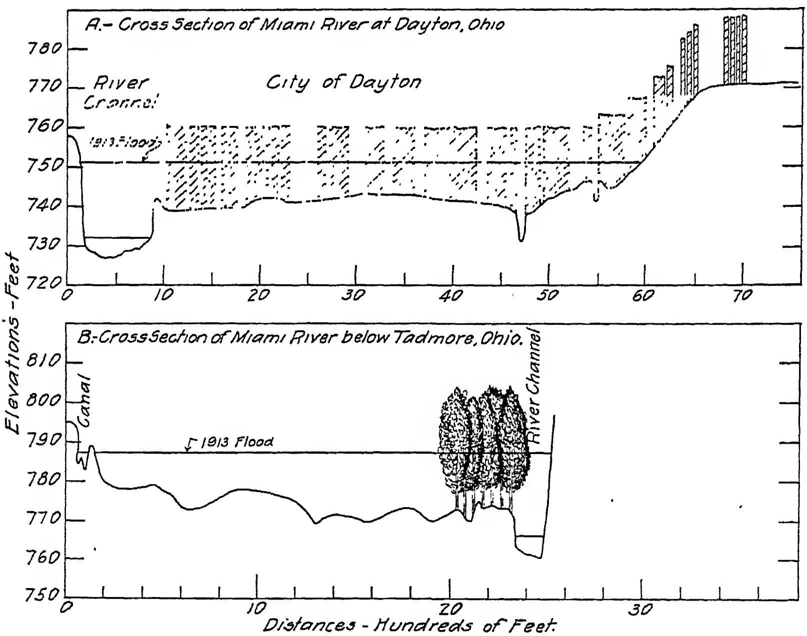


FIG. 316.—Extent of Overflow from the 1913 Flood.

[1] Report of Chief Engineer, Miami Conservancy District, Vol. 1, p. 26, 1916.

[2] Diagram A from Eng. News, Jan. 4, 1917. Diagram B from Rept. Chief Engr., Miami Conservancy Dist., Vol. 1, p. 68, 1916.

settlement of every country the lands first occupied are those that are most convenient and favorable for habitation, agriculture, commerce, manufacturing and other uses. Submerged lands or lands subject to frequent overflow are at first ignored, and those subject to occasional overflow may be settled and be abandoned when such overflow occurs, or are occupied on account of their otherwise desirable character or location in spite of the occasional troubles and losses entailed.

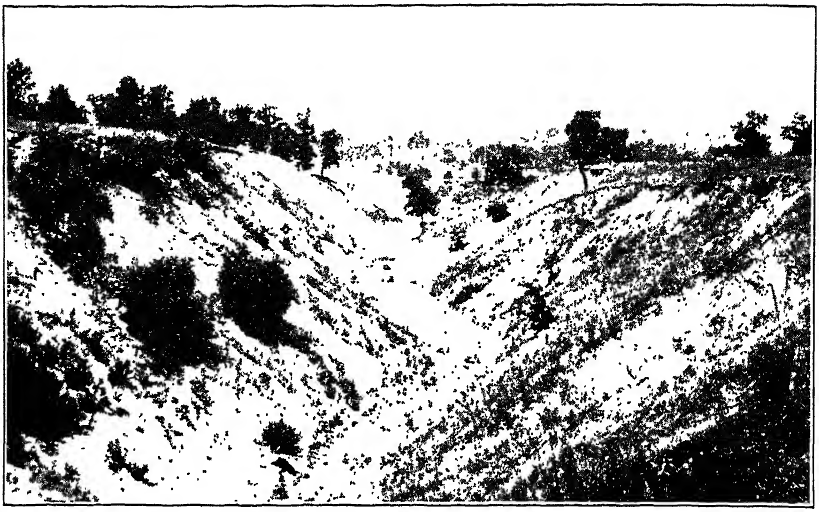


FIG. 317.—Gully Erosion near Janesville, Wis.

As communities develop, the existing settlements attract other settlers and the demands for additional area for habitation, manufacturing and agriculture increase land values. Channels that are only occasionally occupied by the streams and low bottom lands are filled and built upon; bridges are built often without provision for extreme floods; and even the normal channels are sometimes so restricted (Fig. 276, page 465) that the ordinary floods must rise in height in order to create the increased velocity needed to carry the water through the reduced channel. In many cases the channels of streams through farming districts become restricted to a greater extent than those through cities. Improper methods of cultivation and the diversion of minor drainage to new channels often result in undue erosion (Fig. 317) and cause the washing into the streams of large quantities of sands and gravels which congest the channels (Fig. 318). Caving banks carry stumps and trees into the stream, and the channel is also frequently used as a convenient

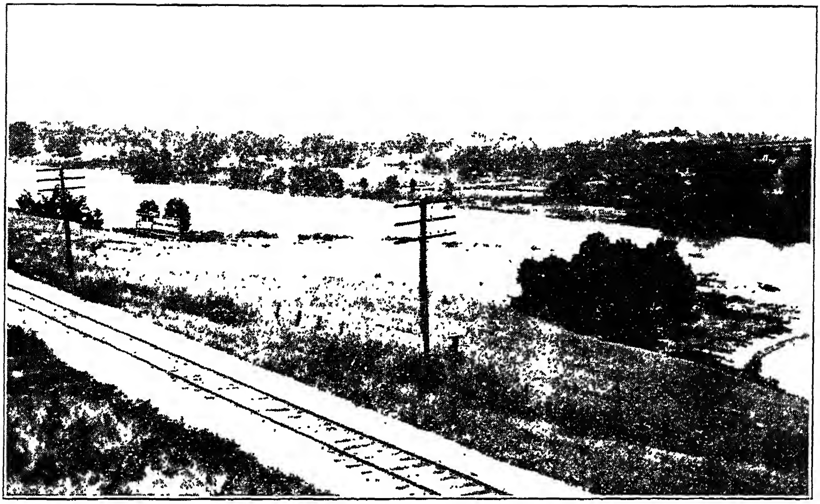


FIG. 318.—Bar Formed in the Rock River above Janesville, Wis., due to Erosion shown in Fig. 317.

dumping ground. The result is undue congestion which often becomes manifest only under extreme flood conditions (Table 57).

TABLE 57.

Present Channel Capacities at Various Loations in the Miami Valley Outside of Towns and Cities, Compared with the 1913 Flood Discharge.[3]

Stream	Location	Channel Capacity Second Ft.	Flood Discharge Second Ft.	Ratio Per Cent
Mad River	West of Springfield ...	5,000	55,400	9.0
Mad River	Below Osborn	6,500	75,700	8.6
Stillwater River..	Above Covington	1,200	33,100	3.6
Stillwater River..	Below Covington	6,000	51,400	11.7
Stillwater River..	Above West Milton ...	7,000	86,200	8.1
Loramie Creek...	N. W. of Lockington ..	1,600	25,500	6.3
Miami River	Above Sidney	5,000	34,100	14.7
Miami River	Above Sidney	5,000	48,500	10.3
Miami River	Below Piqua	10,000	70,000	14.3
Miami River	Tadmor	8,000	127,300	6.3
Miami River	Below Dayton	25,000	252,000	9.9
Miami River	Below Miamisburg	35,000	257,000	13.6
Miami River	Below Hamilton	25,000	352,000	7.1
Miami River	Below Miamitown	20,000	384,000	5.2
Twin Creek	West of Germantown ..	3,000	66,000	4.5

[3] Report Chief Engineer, Miami Conservancy District, Vol. 1, p. 25, 1916.

244. Great Floods and Flood Losses.—The damages occasioned by floods are notable on account of their sudden and serious character, and while it is probably true that the financial losses occasioned by floods are not in the aggregate so large as those occasioned by droughts yet the latter are less obvious or determinable and in general more difficult to prevent. Floods destroy property and life, and losses are direct and measurable. The effects of their recurrence and often of their first occurrence can be obviated by proper protective measures, although in general the shortsightedness of a community in this regard is overcome only after actual flood losses have been experienced.

As examples of the serious nature of flood problems and the necessity of betterments to prevent the recurrence of such disasters, the following data are given concerning a few floods of comparatively recent times.[4]

In 1791 Great flood occurred in Cuba and some 3,000 lives are said to have been lost.

In 1811 Some 24 villages were swept away by a great flood of the Danube in Hungary.

In 1813 Some 10,000 lives were lost by floods in Austria, Hungary, Poland and Silicia.

In 1824 Ten thousand lives were lost in St. Petersburg and Cronstadt from a flood of the Neva.

In 1851 The Yellow River of China burst its banks and changed its course for almost 600 miles, changing its point of discharge from the Yellow Sea to a point 200 miles north in the Gulf of Chili.

In 1856 Flood damaged the south of France to the extent of $28,000,000.

In 1874 One hundred forty-four persons were drowned by a flood accompanied by the bursting of a dam on Milk River, Mass., and 220 lost their lives in floods in Western Pennsylvania.

In 1889 Much of Johnstown, Pennsylvania, was destroyed by a flood which broke the dam on the Conemaugh River, many lives were lost and property worth several million dollars was destroyed.

In 1903 A great flood occurred in Kansas City and on the Mississippi River, causing a loss of many millions of dollars. Heppner, Oregon, was also destroyed with a loss of about 300 lives.

In 1910 The Seine flooded Paris and caused a loss of over $200,000,000.

In 1911 A flood in Freeman's Run caused the failure of a storage

[4] Floods—Encyclopedia Americana.

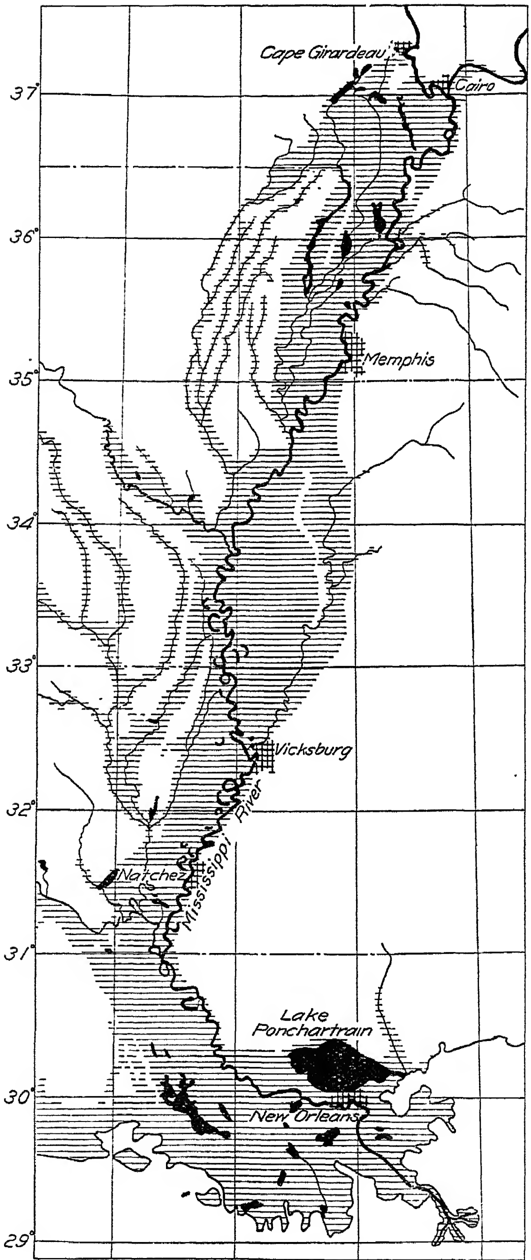


FIG. 319.—Alluvial Flood Plain of the Lower Mississippi River (see page 550).

dam with the loss of 87 lives and the destruction of most of the Village of Austin, Pennsylvania. Extensive floods causing heavy losses were also experienced on various rivers in Wisconsin.

In 1913 Great floods occurred in Eastern United States. In the great Miami Valley about 400 lives were lost and property valued at about $100,000,000 was destroyed.

The history of the great plains of China from Peking to the Yangste River for the last four thousand years is replete with the occurrence of floods in which have been lost literally many millions of lives. The history of the settlement of the lower Mississippi Valley is a continued story of loss of life and property by the almost yearly overflow of that river. In some cases floods have been accentuated by the sudden release of stored waters from improperly designed dams and reservoirs, and occasionally this has been the controlling cause of the great loss of life and property.

Much can be done toward alleviation and prevention of these conditions by intelligent engineering works if supported by enlightened public opinion. The great increase in these losses with the development and growth of the country is creating a constant demand for such betterments.

245. **Floods of the Lower Mississippi Valley.**—The greatest flood problem in the United States is that of the Lower Mississippi Valley. (Fig. 319.) This great valley on account of its accessibility by navigation, its fertile flood plain and temperate climate attracted settlement at an early date. The settlement of these lands and their frequent inundations by the floods of the river have caused almost annually great losses in property and frequent losses of life. This resulted in early attempts at local betterments which have later been organized into more consistent efforts through state and district levee boards and later by government assistance through the Mississippi River Commission.

The total amount expended on the levees of the lower Mississippi up to 1914 was about ninety-seven million dollars of which the United States expended thirty-one millions. Up to June, 1913, the total expenditures of the United States on this portion of the river was about seventy million dollars.[5] The early works of protection were limited in extent and the levees were only sufficient for protection against moderate floods. Even at the present day the levees have not been

[5] Hearings on Bill S. 2, To prevent floods on the Mississippi River, Committee on Commerce, U. S. Senate, 63d Cong., 2d Session, pp. 137–175.

built to an elevation sufficient to provide for the maximum flood height which must be expected when the works are finally completed and rendered permanent by proper revetment and other bank protection. The occasional great floods obtain at intervals averaging about once in six years (see Floods of +50 feet at Cairo, Fig. 320), although it will be noted that they sometimes follow each other annually for two or three years. These great floods have frequently destroyed miles of levees and inundated great sections of the alluvial valley. The area of the alluvial flood plain of the Lower Mississippi subject to overflow

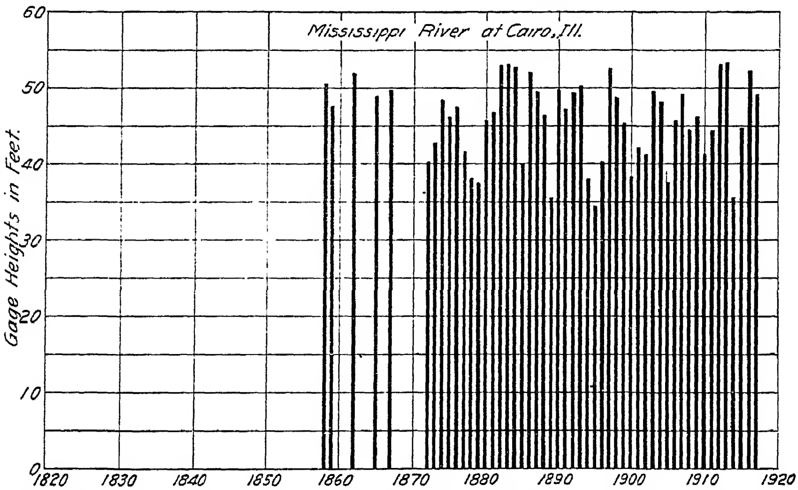


FIG. 320.—Maximum Annual Gage Heights on the Mississippi River at Cairo, Ill.

prior to the construction of the levee system is estimated by the Mississippi River Commission at 29,790 square miles (Fig. 319). The flood of 1897 inundated 13,578 square miles and that of 1913 about 10,812 square miles.

The ordinary floods of the Lower Mississippi are caused by the normal floods of its various tributaries, the Upper Ohio, the Tennessee, the Upper Mississippi, the Missouri Rivers and many minor streams. When the normal spring floods on these various tributaries fail to synchronize near their crests the floods on the lower river reach only normal heights, but where exceptional rains produce high flood conditions on one or more of these tributaries and these floods synchronize with ordinary floods on other tributaries, exceptional floods result in the lower river. The heights of the maximum annual floods at certain stations on the Mississippi River and its tributaries are shown in

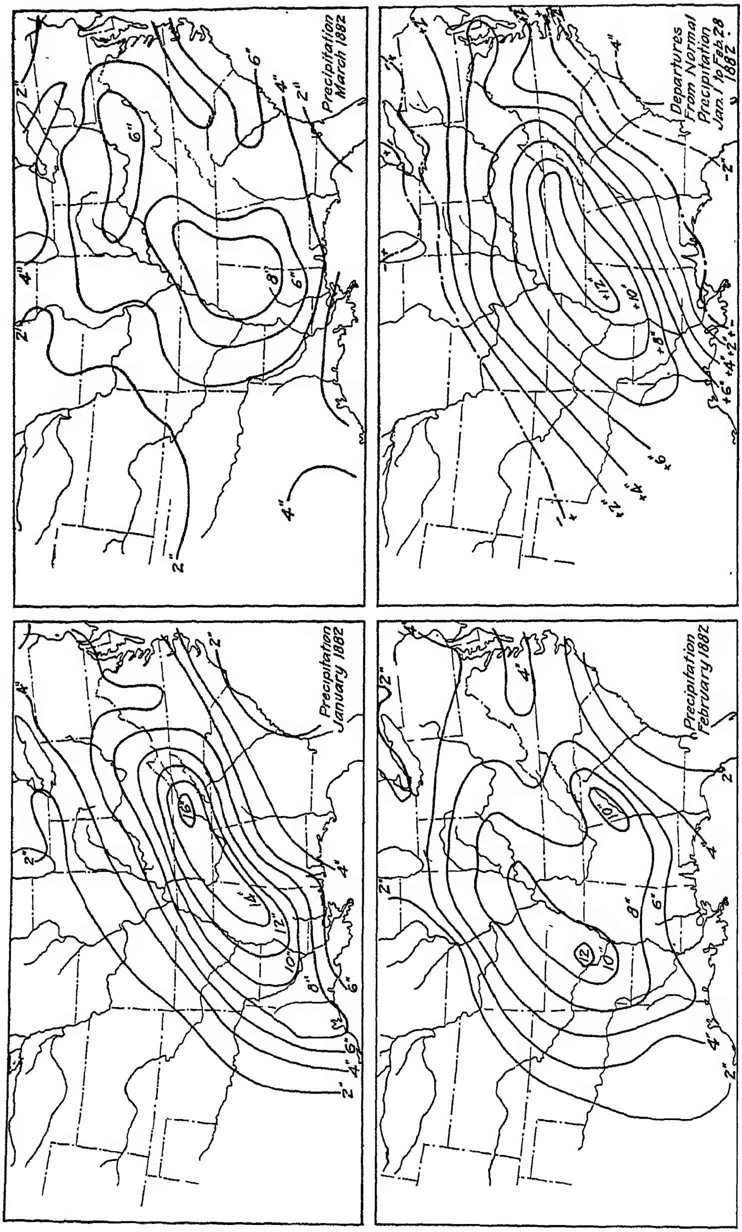


FIG. 321.—Rainfall Conditions which caused the Flood of March 1882 at Cairo, Ill. (see page 553)

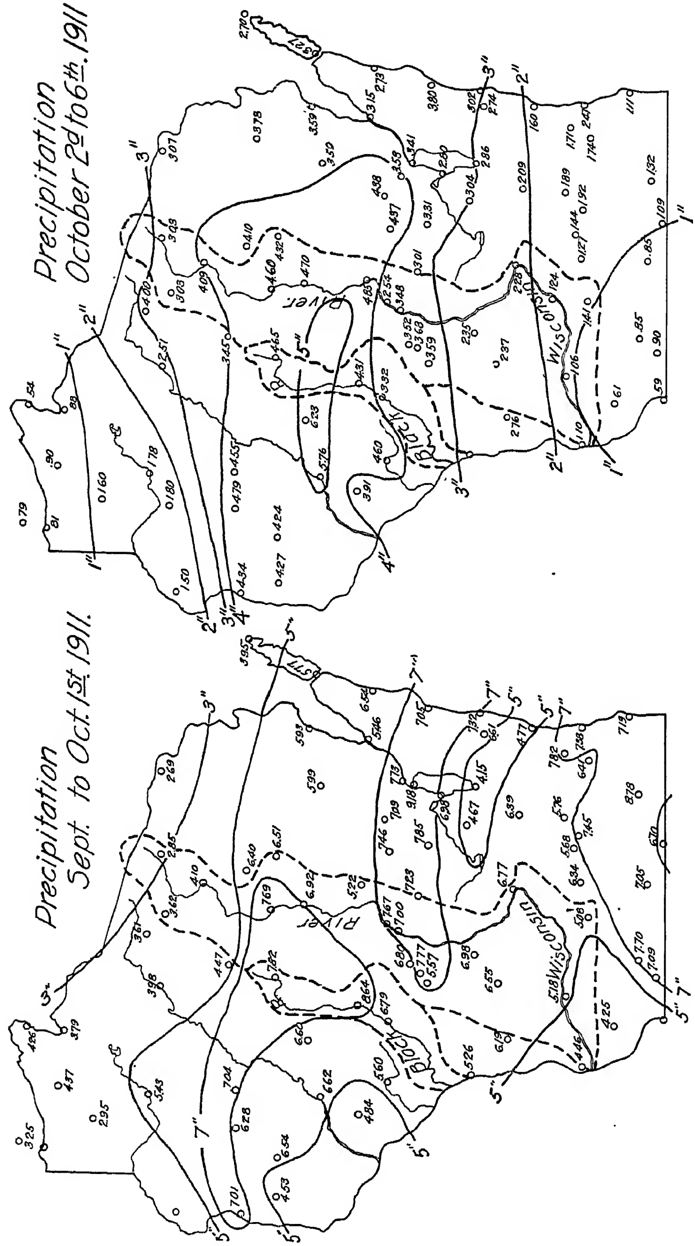
Figs. 320 and 327. The relative gage heights at various stations on the tributaries, and the resulting gage heights at Cairo, are shown in Fig. 326, and the rainfalls producing the flood of 1882 together with the departure of the rainfall from the normal are shown in Fig. 321.

246. Floods of October, 1911, in Wisconsin.—The autumn flood of October, 1911, on the Wisconsin River was one of the most severe on record for that river. In general floods on the Wisconsin occur in the spring (Fig. 327, p. 562). When fall floods occur they are always due to a saturated condition of the drainage area from earlier rains followed by an unusual intense concentrated rainstorm. In this case the rainfall of October 2 to 6 was preceded during the thirty days from September 3 to October 1, 1911, by a somewhat heavy precipitation, the distribution of which is shown in Fig. 322 A. The heaviest rainfall of October 2 to 6 extended across the upper portion of the Black River Valley and as a broad band across a portion of the Wisconsin River Valley (Fig. 322 B)) The heaviest portions were south of the headwaters of the Wisconsin River (see also Fig. 200, p. 339) where a reservoir system has been constructed.

The progression of the flood wave from this storm is shown by hydrographs for different points along the Wisconsin River in Fig. 287, p. 493. At Rhinelander, above which most of the reservoirs on the river are constructed, there was practically no flood. In this flood a dam just below Wausau went out (Fig. 5, p. 27) which undoubtedly was one of the causes of the extra rise at Knowlton. At Grand Rapids the flood peak followed a little later. Some of the flood gates at that point were blown out which added somewhat to the flood heights below that point. At Prairie du Sac, where the plant of the Wisconsin River Power Company was under construction, the work was flooded, the cofferdam destroyed and a large loss entailed.

The greatest flood loss from this storm occurred on the Black River. The first casualty was the failure of the earth dike of the Dells reservoir dam. This reservoir was used for storing water for power purposes and impounded about 10,000 acre feet. The dam consisted of a concrete section and spillway and of an earthen dike with a concrete core wall. The break was occasioned by the over-topping of the earth section due to inadequate spillway capacity. The concrete section was left intact but the earthwork with its core wall was destroyed. The failure of this reservoir resulted in the overtopping of the earth section of the reservoir at Hatfield, about 4½ miles below.

The Hatfield dam consisted of a concrete spillway about 50 feet in height on both sides of which was an earth embankment. The spill-



A B

FIG. 322.—Distribution of Rainfall causing Wisconsin Floods of October, 1911 (see page 553).

way which was some 490 feet long was adequate for any normal flood in the river and passed about 12 feet of water before the east embankment was overtopped and destroyed. The flood waters, when they passed over the earth section, washed out 500 feet of reservoir embankment and about the same length of the Green Bay and Western Railroad which crossed the Black River at this point. A view of the site of the destroyed earth section at Hatfield, taken some time after

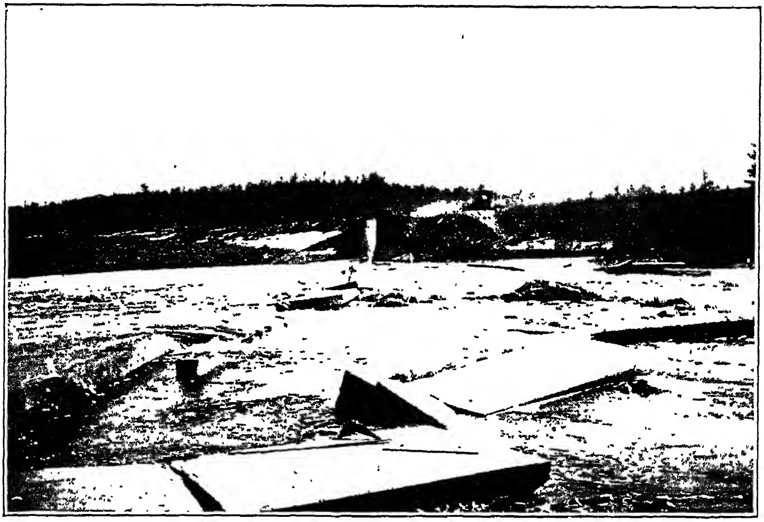


FIG. 323.—Break in Earth Embankment at Hatfield Dam.

the flood, is shown in Fig. 323, and the water from these reservoirs together with the normal flood of the Black River sweeping down on the City of Black River Falls about 12 miles below Hatfield, caused great damage in that city.

The dam at Black River Falls during the flood of June, 1911 (Fig. 324), carried about 10,000 cubic feet per second with the spillway more than filled. A normal high flood flow of about 40,000 cubic feet per second must be expected at Black River Falls under extreme conditions and without floods from breaking reservoirs. The north abutment of this dam entered a natural bank of earth but did not reach rock (Fig. 192, p. 333). The October flood perhaps 80,000 second feet, cut entirely around the north end of the dam and overflowed the business district of the City. The view of the flood entering the city (Fig. 325) shows a three-story hotel with a portion of its walls just

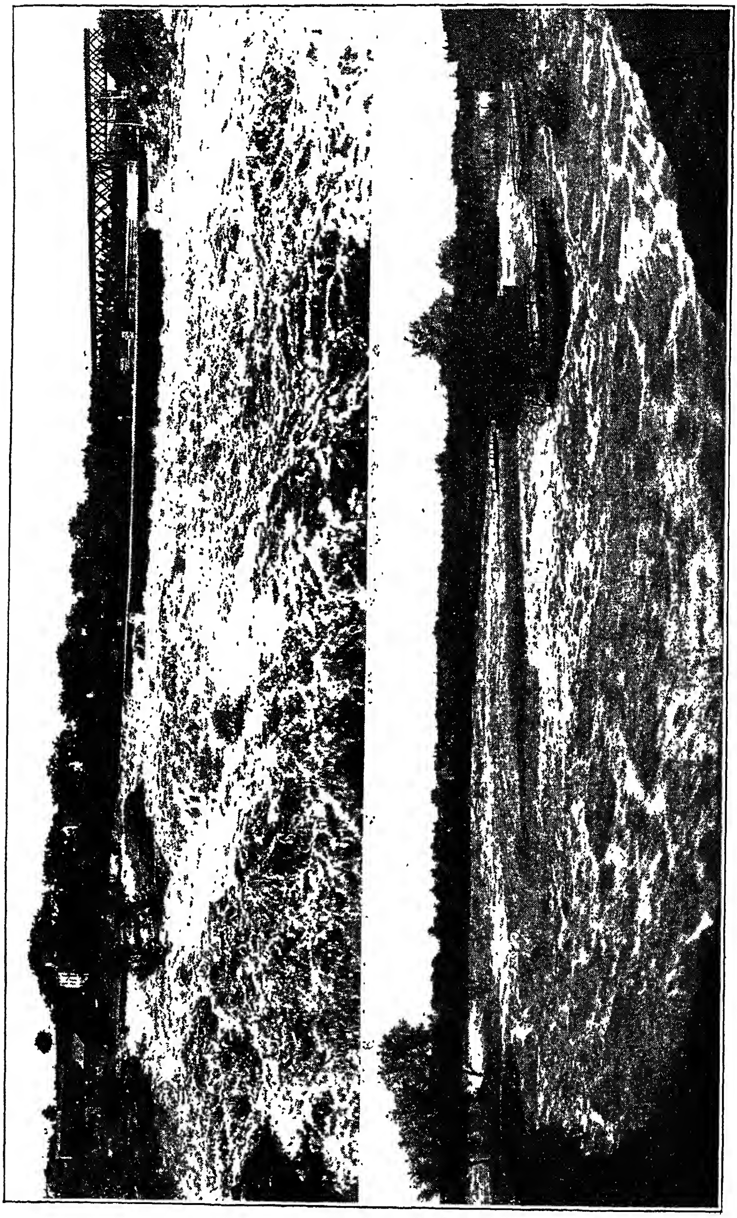


FIG. 324.—(Upper) Black River Falls During the June Flood, 1911.
(Lower) North End of Dam Early in October Flood, 1911.

falling into the river. The buildings in the business portion of the city, resting on sand foundations, melted into the stream and disappeared, and the flood destroyed not only the buildings and their foundations but the land was entirely washed away for about two blocks in width and for several blocks in length (Fig. 194, p. 334). The wooden mill building (Fig. 325) which rested on a rock foundation was not seriously injured. Perhaps the best understanding of the nature of

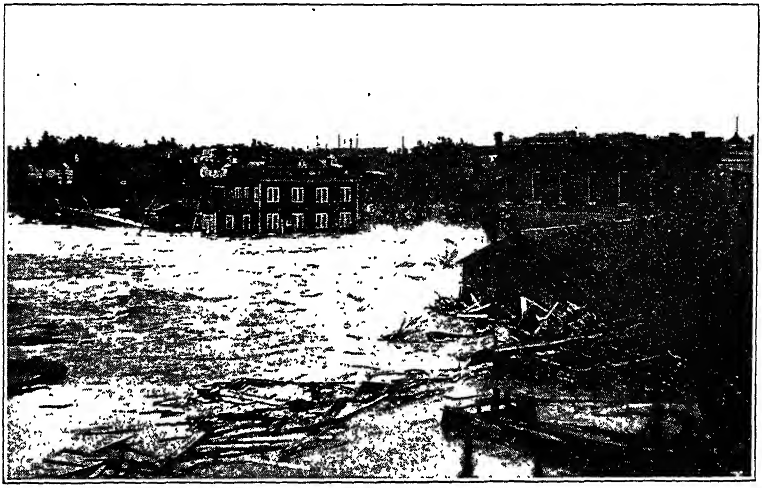


Fig. 325.—Flood of October 1911 Entering the City of Black River Falls.

the catastrophe can be gained from Fig. 193, p. 334, showing the city before and after the flood.

247. **Other Flood Problems of the United States.**—There are many serious flood problems in the United States and comparatively little has yet been done toward their solution. About 1,700 square miles of the valley of the Sacramento River in California has been subject to frequent and serious overflow. This problem has been studied by various commissions in 1880, 1894, 1904 and 1910 and a considerable difference in opinion developed as to the best methods for its solution. The question has now been settled and some work is being done along the lines adopted by the State and Federal authorities. This problem is only second to that of the Lower Mississippi Valley.[6]

The great loss in the Miami Valley due to the flood of 1913 has resulted in the formation of the Miami Conservancy District, and the

[6] Flood Control, H. M. Chittenden, International Engineering Congress 1915, Waterways and Irrigation, p. 157.

preparation of the most comprehensive plans for the flood protection of that valley that have yet been attempted in any country.[7] These works are now (1919) under construction.

The rainfall which caused the great flood of March, 1913, is discussed and illustrated in Sec. 129, p. 266 et seq. and the flood conditions at Dayton are shown in Figs. 10 and 11, p. 40. The City of Columbus and other cities in the Valley of the Scioto River suffered seriously in the same flood and preliminary plans for protecting works have been made,[8] but differences in opinion as to the nature and character of the work have arisen which have prevented the consummation of the plans.

The City of Pittsburg has suffered seriously from the flood of the upper Ohio and its tributaries, and comprehensive studies have been made of its flood problems[9] but nothing material has yet been done toward permanent flood relief.

At Kansas City the bottom lands along the Kaw River, which are the center of transportation, commercial and industrial activity, were damaged to the extent of over $30,000,000 and a loss of 19 lives in the flood of 1903.[10] While agitation for flood protection has been constantly maintained ever since that date no comprehensive plan has yet been carried into effect, largely on account of divided jurisdiction.

248. The Cause of Floods.—The causes that produce runoff and its variations have been discussed in Chapters XVI and XVII. The causes of high water, excessive runoff or floods should be evident from that discussion and may be summarized as follows:

1. Floods will occur on a given drainage area when the following conditions obtain at one and the same time, and will increase in intensity and duration as the conditions become more favorable to increased runoff.

A. When the rainfall on the drainage area is of:

a. Great intensity
b. Wide distribution
c. Long duration

[7] See Report of A. E. Morgan, Chief Engineer, Miami Conservancy District, Dayton, Ohio. Also various Bulletins published by the Miami Conservancy District.

[8] See Report on Flood Protection of Columbus, Ohio, by J. W. Alvord and C. B. Burdick, 1913. Also Report on Flood Relief for the Scioto Valley, by J. W. Alvord and C. B. Burdick, 1916.

[9] See Report of Flood Commission of Pittsburg, Pa., 1911.

[10] See The Floods of the Spring of 1903 in the Mississippi Watershed, Bul. M, U. S. Weather Bureau, 1904.

B. When the surface of the drainage area is impervious from:
  a. Saturation by previous rainfall
  b. Frozen condition of ground
  c. Normal geological structures

C. When retention is at a minimum on the drainage area from:
  a. Cool weather
  b. Absence of vegetation
  c. High humidity

In addition to the above, floods sometimes result from or are augmented by ice and log jams and the failure of reservoir dams.

2. In the comparison of floods on different drainage areas other factors are important: Topography, geology, arrangement of tributaries, surface conditions, location relative to storm paths and sources of vapor, climatic conditions, temperatures, wind velocities, etc.

The maximum floods on all streams are due to a storm or a series of storms that have covered the drainage areas so as to produce a synchronism in the discharge of the various tributaries whereby the maximum flood accumulates at the locality under consideration. The conditions preceding maximum floods are more apparent from a study of the larger streams where numerous data are available. Fig. 326 shows various hydrographs of the Mississippi River at Cairo during the six maximum recorded floods that have occurred at that place. For each flood at Cairo comparative hydrographs are shown of the Upper Ohio at Cincinnati, of the Tennessee River at Chattanooga and of the Mississippi River at St. Louis. The elements of flow conditions at these various stations are given in Table 58.

TABLE 58.

Elements of Flow Conditions at and Above Cairo.

Gaging Station	River	Drainage Area Above Station Sq. Miles	Flood Stage Feet	Height in Stage Feet	Lowest Stage Feet	Distance Above Cairo Miles
Cincinnati, Ohio ..	Ohio	72,684	50	71.1	1.9	500
Chattanooga, Tenn.	Tennessee	21,418	33	58.6	0.0	505
St. Louis, Mo.	Middle Miss. ..	699,000	30	41.4	—3.1	191
Cairo, Ill.	Ohio	203,900	......	......	......	......
	Mississippi ...	712,700	45	54.8	—1.0	......

A comparison of these six great floods with the normal spring flood at Cairo is shown by their hydrographs in Fig. 329, page 565.

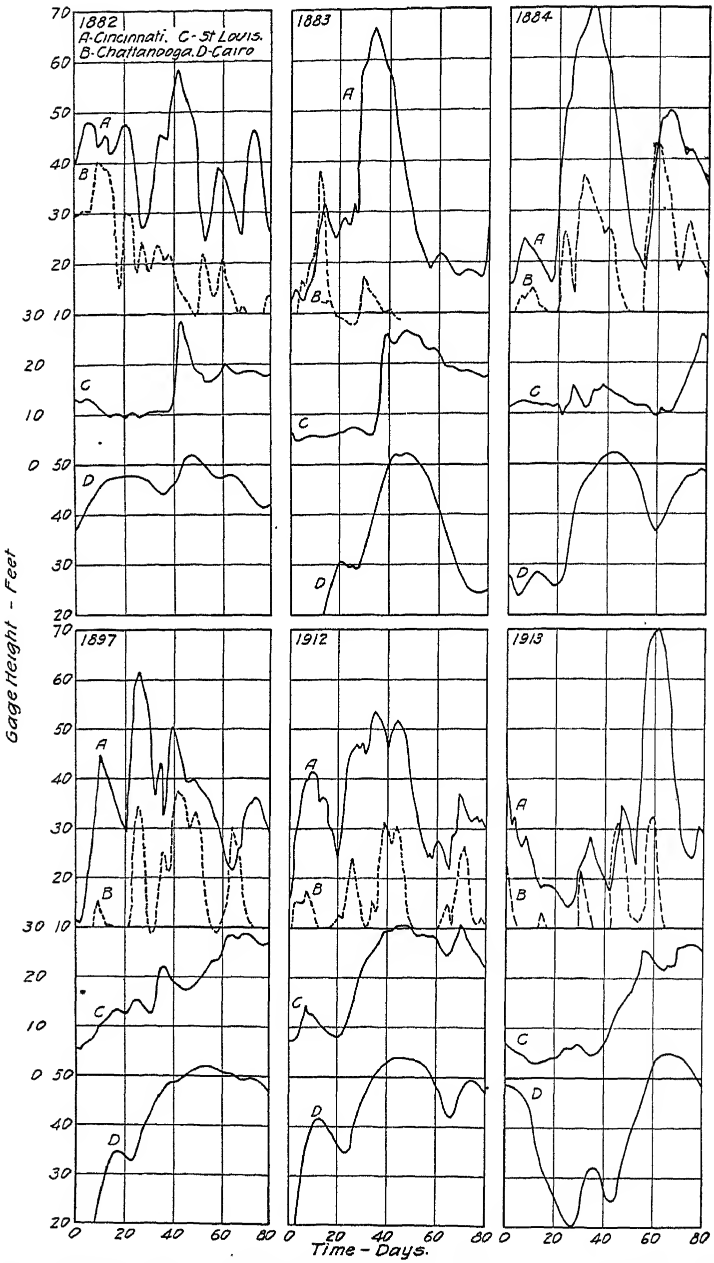


FIG. 326.—Hydrographs of Mississippi River at Cairo and of Various Tributaries during the Six Maximum Floods at Cairo.

From Fig. 326 it is evident that the crests of the various floods at Cairo are due to high water in the tributaries as follows:

1882	Upper Ohio and Middle Mississippi
1883	Upper Ohio and Middle Mississippi
1884	Upper Ohio and Tennessee
1897	Upper Ohio, Middle Mississippi and Tennessee
1912	Upper Ohio, Middle Mississippi and Tennessee
1913	Upper Ohio, Middle Mississippi and Tennessee

The frequent and excessive floods of the Ohio River result from the fact that the normal tracks of storms from the southwest parallel its course. (See Fig. 153, p. 274 and Fig. 321, p. 552).

In all cases it is noticeable that the floods in the Upper Ohio dominate the Cairo floods and the exceptional floods are produced by a combination of floods in the Upper Ohio with those from one or more of the other large tributaries. It is also evident that if a flood ever occurs that combines high water in the Mississippi River, such as occurred in 1844 at St. Louis (Fig. 326, p. 560) with high water in the Ohio such as occurred at Cincinnati in 1884, together with the high water that has occurred on the Tennessee or some of the other minor tributaries, Cairo will experience a flood of a magnitude materially greater than has as yet occurred within the period of the limited records.

An interesting and instructive extension of this study can be made by adding to these diagrams hydrographs of other large tributaries to the Mississippi River or by confining the study to several of the minor tributaries and the main tributary into which they flow.[11]

249. Time of Occurrence.—Any series of hydrographs showing the daily runoff from a drainage area (Fig. 284, page 488) will show periods of high flow which ordinarily occur at more or less certain dates but vary considerably in quantity, and consequently in crest height. If the series examined covers a long term of years, occasional floods will be found to have occurred at dates quite remote from the date of common occurrence.

In general through the northern part of the United States normal floods occur in the spring, for while at that season normal rainfall is less in intensity, distribution and duration, than during the summer, the ground is then more impervious, evaporation is at a minimum, and ground flow from the stored water of winter is at a maximum. Nevertheless observation will show that occasionally on some streams in these parts of the country even higher floods occur at other periods on account

[11] Daily River Stages on the Principal Rivers of the United States, Parts I to XVI, U. S. Weather Bureau. Gives gage heights from the earliest records to and including 1917.

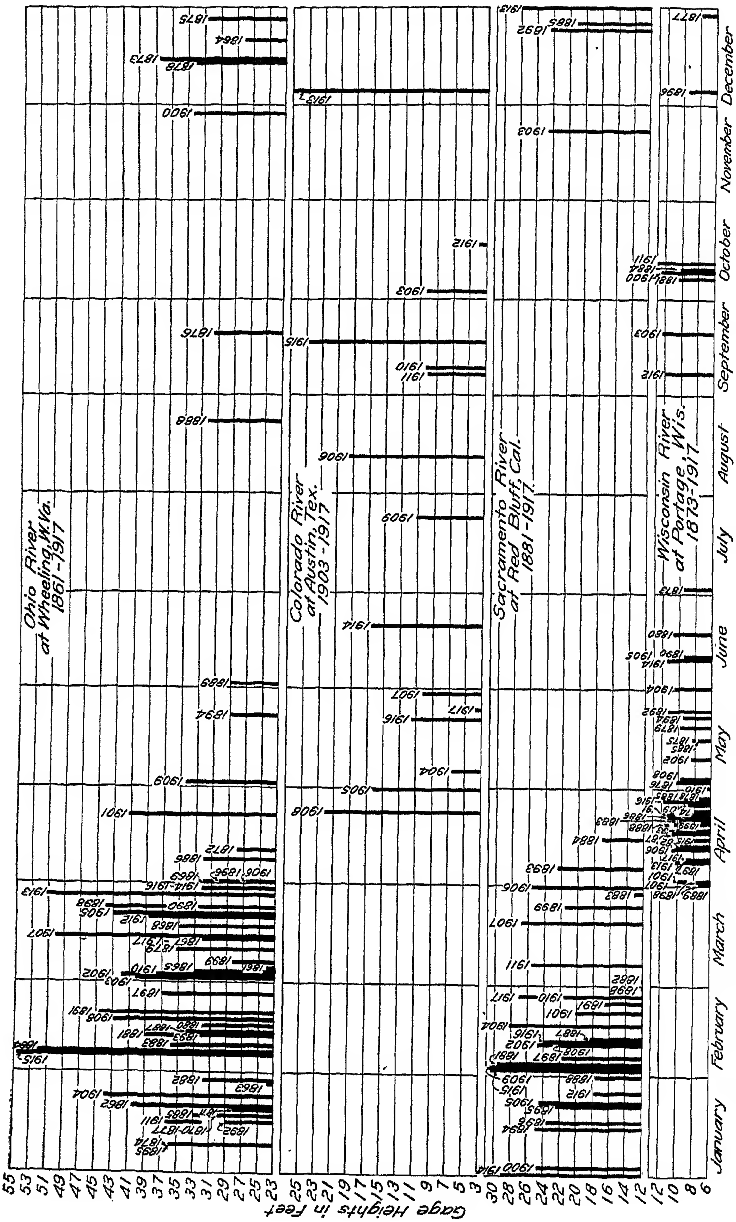


FIG. 327.—Time of Occurrence and Maximum Gage Heights of Annual Floods

of occasional abnormal conditions of ground saturation and rainfall. Fig. 327 shows the relative dates of occurrence and height of the maximum annual floods on various rivers of the United States.

250. Relative Time of Occurrences of the Flood Crest in Rivers.— In a rising river the advance of the the peak of the flood wave does not in general represent the velocity of the flowing waters (Fig. 287, p. 493). When a flood advances from the head waters of a stream the advancing wave must first fill up the river channel or immediate valley to the flood line, hence the peak of the wave at any point farther down the river is in general caused by water that has passed any upstream point at a time later than the occurrence of the flood crest.

When the flood is caused by rains or melting snow more or less general in extent, the flood wave may be caused by the local runoff or by combined local and headwater runoff, and the peak of the flood crest in the lower valley may occur earlier or may be simultaneous with the flood crests at points on the upper river. (Fig. 328).[12] The relative time of the flood crest therefore is entirely a matter of distribution of the rainfall or snow that produces the flood and of the flood channel capacity.

Occasionally the sudden advent of large bodies of water into a pool or river of low gradient, such as is occasioned by a sudden flood passing a high dam into a pool below, will set up waves of translation which move with high velocities and much faster than the flowing water. These sometimes progress upstream in opposition to a river flow as in the case of the arrival of a tidal wave at a river mouth. Mr. Wm. J. McAlpine[13] states that a wave of translation in the Black River, occasioned by the failure of a dam, passed from Lyons Falls to Carthage, a distance of 40 miles, in two hours, while the flood wave did not reach Carthage until six hours after it first passed Lyons Falls. He also states that the sudden discharge of water over the dam at Lowell on the Merrimac River due to the closing of the wheels on Saturday nights, causes a rise of water fifteen minutes later at Lawrence, thirteen miles below, although floats require twelve hours and more for their passage. Mr. J. Scott Russell[14] uses the formula given in Sec. 52, p. 92, to calculate the velocity of such waves in canals and rivers. (See also Sec. 58, p. 105.)

[12] From unpublished data, Miami Conservancy District, by permission of A. E. Morgan, Chief Engineer.

[13] Waves of Translation in Fresh Water, Wm. J. McAlpine, Trans. Am. Soc. C. E., Vol. 1, p. 383.

[14] Beardsmore's Hydrology, p. 211.

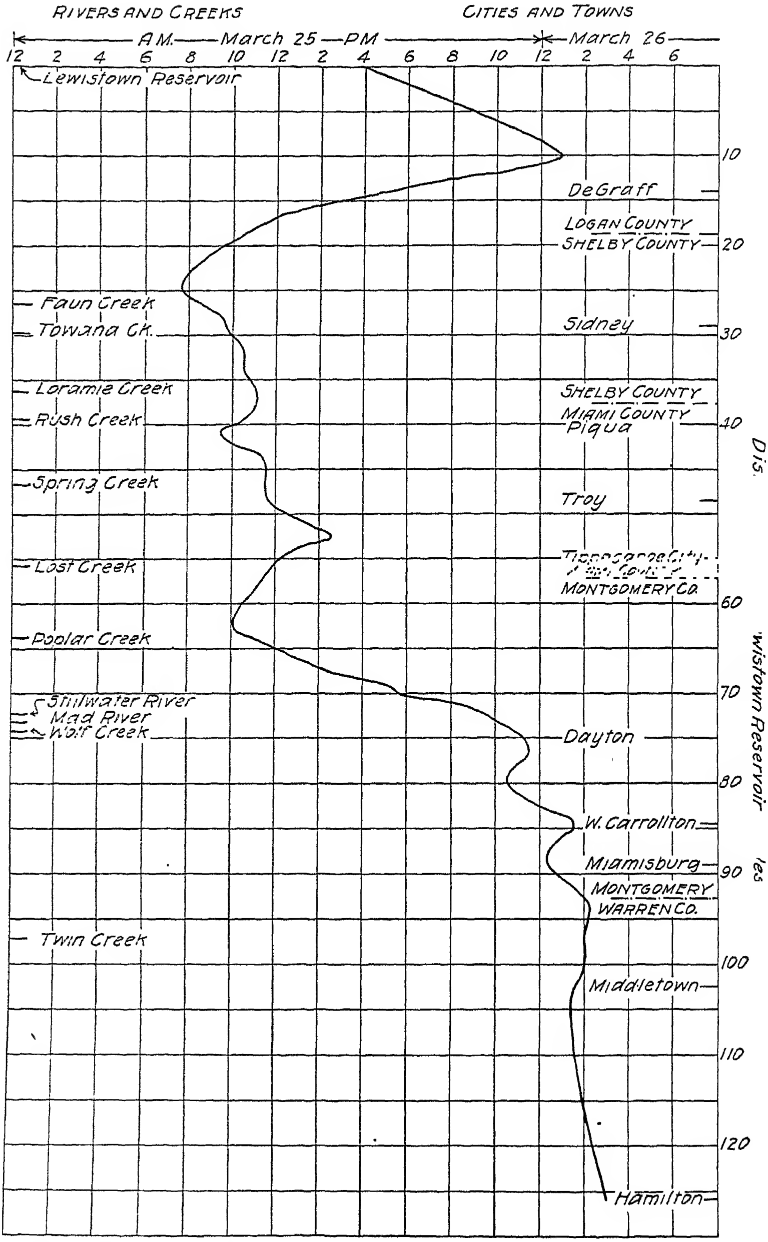


FIG. 328.—Time of Occurrence of the Flood Crest at Various Points on the Great Miami River during the Flood of March, 1913 (see page 563).

251. The Rise, Duration and Recession of Floods.—In the occurrence of floods, the time which is taken for the flood wave at any point to rise to its peak, its duration at and above the flood stage, and the time required for it to recede depend particularly upon the size and shape of the drainage area, the arrangement of the tributaries, the storage, and on the distribution, duration and intensity of the rainfall producing it. The floods in large rivers usually rise slowly, endure for a

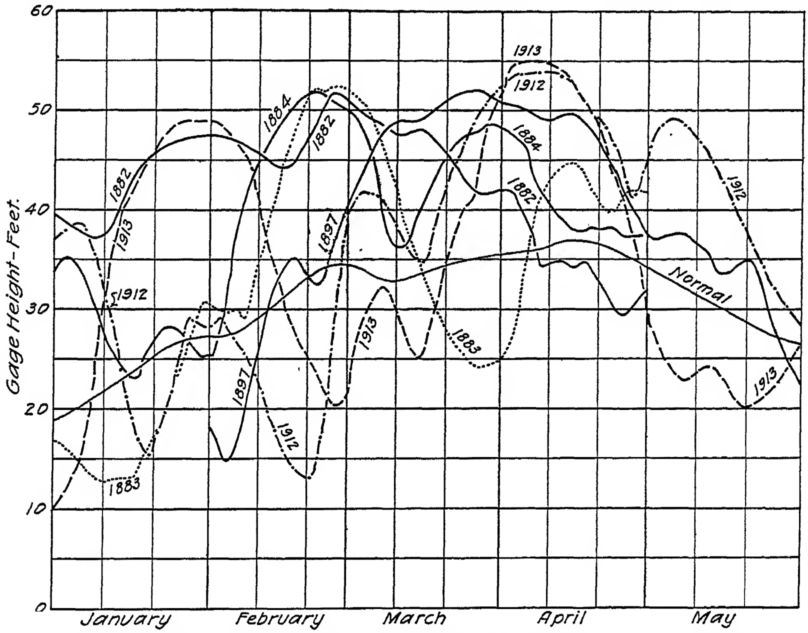


FIG. 329.—Comparative Gage Heights of the Six Maximum Floods at Cairo, Ill.

considerable period and slowly recede, while in small streams the rise is rapid, the duration short and the recession rapid. In the great rivers (Fig. 329), each period may be several weeks in extent. In large streams (draining several thousand square miles) the periods are commonly several days (Fig. 330) while in small streams the periods may be only several hours in duration (Fig. 331, p. 567). When no surface or subsurface storage exists on a drainage area, and when a stream has adequate channel capacity (Fig. 184, p. 326) so that there is no overflow and consequent valley storage at flood stages, the time of flood advance and flood recession is approximately equal. In most cases some storage exists and in consequence flood advance is in general more rapid than flood recession. The presence of storage on a drainage area therefore reduces the intensity of the flood peak and prolongs the

duration of the flow (Fig. 337, p. 575). Both the time of occurrence and the duration of floods in any stream vary greatly, however, with the intensity and distribution of the rainfall, and extraordinary floods may depart radically from the normal. (Figs. 330 and 331.)

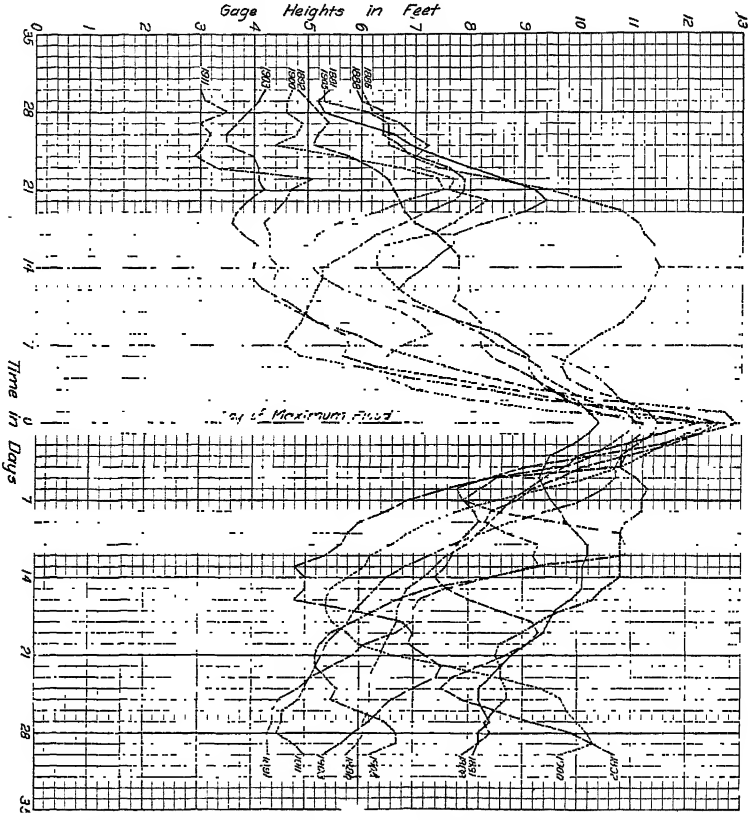


FIG. 330.—Advance, Duration and Recession of Various Floods at Kilbourn on the Wisconsin River.

The relations between the flood waves and the time and amount of the rainfalls producing them are shown for the March, 1913, floods on the Scioto and the Miami Rivers in Fig. 332.

The quantity of flow and the consequent flood height affects the elevation to which levees and other protecting works must be built, and the duration must influence the character of construction in order to minimize seepage and prevent destruction. The occurrence and duration must also modify the size of reservoirs and detention basins, and the peak flow must constitute the basis of spillway design.

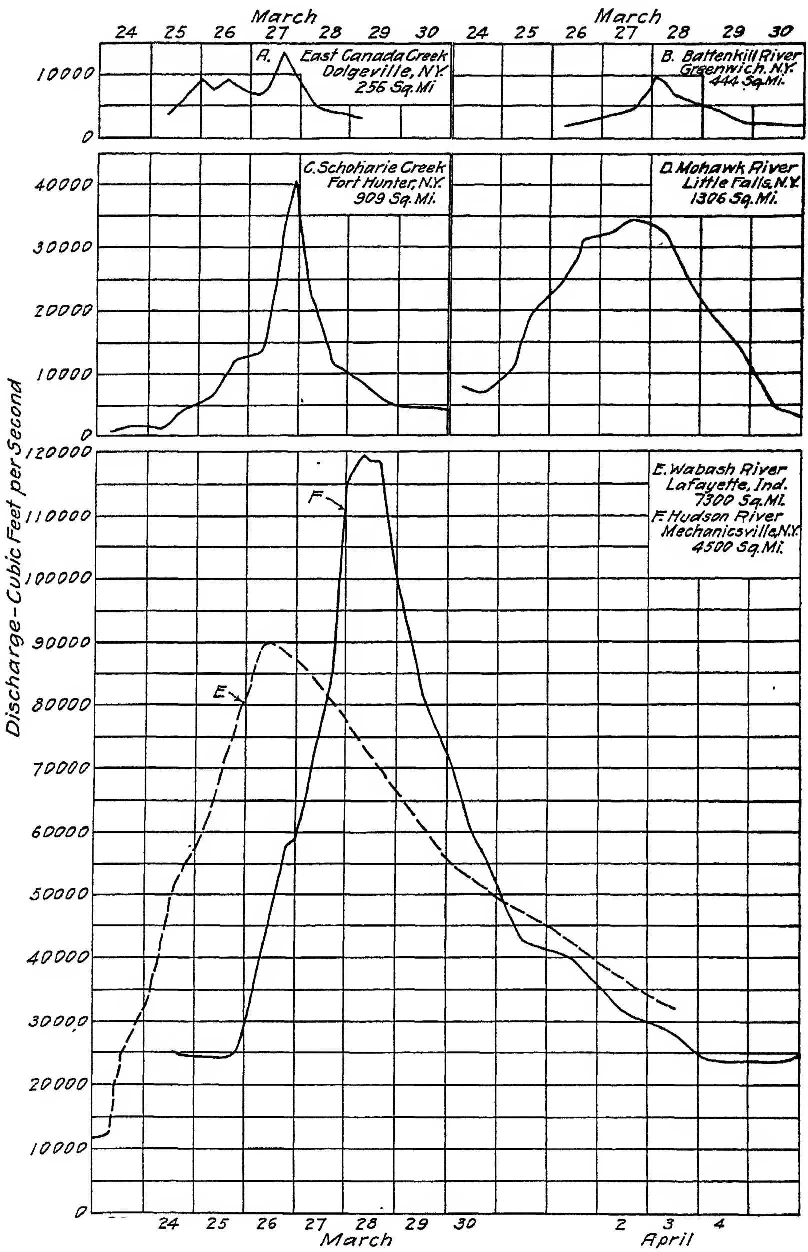


FIG. 331.—Advance, Duration and Recession of Flood Waves of March, 1913, on Various Streams. After R. E. Horton.

The records of flood flows may give the average maximum gage height or discharge for a 24-hour period or the gage height and maximum discharge at the time of the flood crest. The latter will exceed the former by a considerable percentage and the difference in the records should be carefully distinguished. In the flood discharge of great rivers such as the Ohio and the Upper Mississippi River the flow

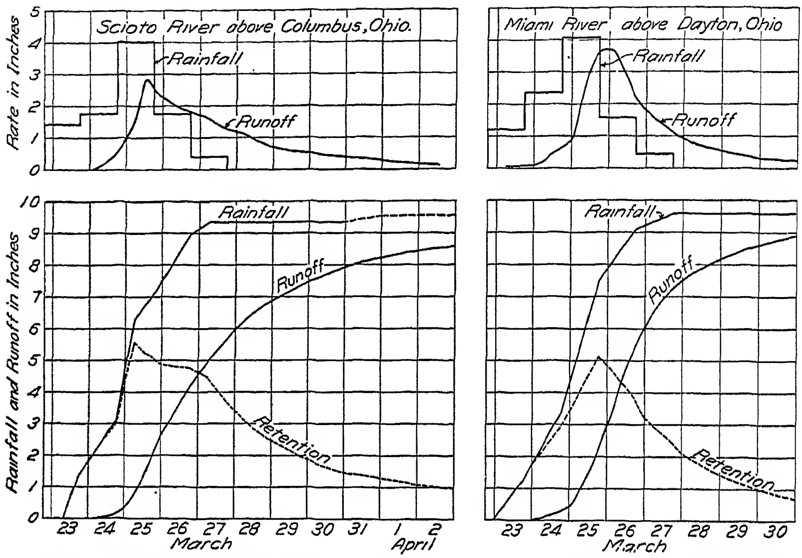


FIG. 332.—Relations of Rainfall and Flood Waves on the Scioto and Miami Rivers for the Floods of March, 1913.

and crest height for the day of maximum flood vary but little from those at the hour of maximum discharge. In small streams, however, there is a great difference between the average discharge for the maximum 24 hours and the discharge at the crest of the flood. The maximum crest height and the maximum crest discharge is most important in certain engineering problems. Mr. W. E. Fuller gives the following approximate expression for the relations of maximum rate of flow to average maximum 24-hour flow.[15]

$$Q\,\text{max.} = Q\left(1 + 2M^{-0.3}\right)$$

in which

Q_{max} = maximum flood discharge in cu. ft. per second
Q = maximum average 24-hour discharge in cu. ft., sec.
M = drainage area of the stream in square miles

15 Flood Flows, W. E. Fuller, Trans. Am. Soc. C. E., Vol. 77, p. 564, 1914.

This formula gives values for the maximum flow in terms of the average 24-hour flow as follows:

Drainage Area Sq. Mi.	Maximum 24-hour Per Cent.	Maximum Flow Per Cent. of 24-hour flow
1.	100	300
10.	100	200
1000.	100	125

This formula, as in the case of all other formulas, must be taken as a general expression to which there are numerous exceptions. For example, the flood in Schoharie Creek in March, 1913, at Ft. Hunter, N. Y. (Fig. 331, p. 567) had a maximum flow of 141% of the maximum 24-hour flow.

252. **Flood Frequencies.**—From the record of past floods it is evident that the average flood to be expected every year is exceeded by floods of less frequency that may occur at intervals of five to ten years, and that these will be considerably exceeded by greater floods which may occur at intervals of from 50 to 100 years, and that still greater floods must be expected at longer intervals. It is to be noted that the intervals mentioned are merely averages, that there is little regularity in the occurrence of floods of great magnitude, and that such great floods may follow each other at lesser intervals but that the average appearance of the greatest floods is rare but uncertain. The highest flood on record at Cincinnati, Ohio, to that date was the flood of 1882. This flood was exceeded by the flood of 1883 which in turn was again exceeded by the flood of 1884 which has not been equalled since that date.

In the 103 years of record on the Rhine[16] (Fig. 333) there has been one flood above 25 feet, seven floods above 24 feet, eleven floods above 23 feet, twenty-eight floods above 22 feet, and fifty-nine floods above 21 feet.

On the Seine River at Paris no flood equal to the flood of 1615 has occurred since that date (Fig. 334)[17] The two floods next in magnitude occurred in 1658 and 1910 respectively, while six floods above 25 feet and fifteen above 20 feet have occurred since 1600.

The great flood of 1913 on the Miami River was preceded by a flood

[16] From Decrease of Water in Springs, Creeks and Rivers, Gustave Wex, Washington D. C., 1880.

[17] Gage Heights on the Seine River at Paris from paper of M. Belgrand Annals du Ponts et Chaussees, 1852, premier semestre, p. 102. Also Report on the Influence of Forests on Climate and on Floods, W. L. Moore, p. 18, and Eng. News, Vol. 63, p. 327, 1910.

almost as great in 1805 while other great floods of lesser magnitude occurred in 1866, 1883 and 1898.

At Cairo, Illinois, located at the junction of the Ohio and Mississippi River (Fig. 319) there have been since 1868 six floods above 52.5 feet, (Fig. 326 and 329) ten floods above 50 feet and thirty-two floods above 45 feet or the bank full stage (Fig. 320).

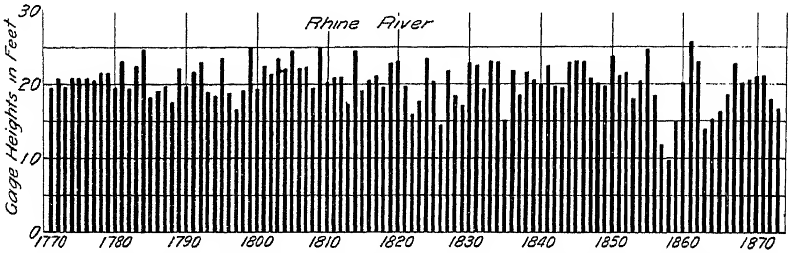


FIG. 333.—Maximum Annual Gage Heights on the Rhine River at Emmerich, Germany. After Wex.

Where records of considerable periods are available the frequency of floods may be considered mathematically, as was the extreme rainfall records in Section 110 to 112 inclusive but such calculations must not be taken too seriously. Mr. L. F. Harza, Engineer of the proposed

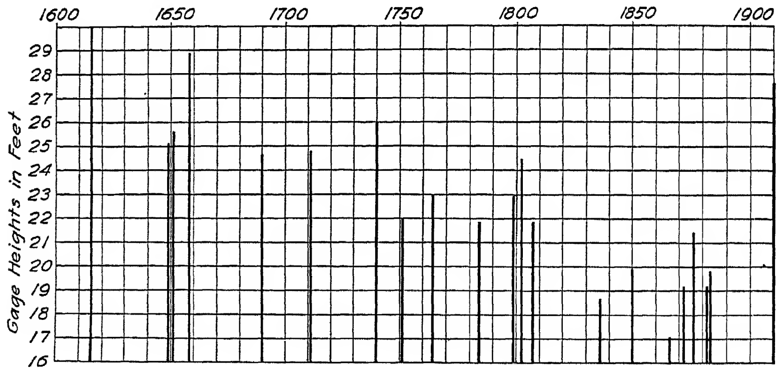


FIG. 334.—Gage Heights of Maximum Floods on the Seine River at Paris, France.

power development at The Dalles on the Columbia River[18] considered the flood flows of the river at the proposed power site by probabilities (Fig. 335) and the results would indicate that the great flood of 1894

[18] Report on Columbia River Power Project near The Dalles, Oregon, L. F. Harza, Project Engineer. Technical Pub. Co., San Francisco, 1914.

Forests and Floods: Extracts from an Austrian Report on Floods of the Danube, H. M. Chittenden, Eng. News, Vol. 60, p. 467, 1908.

would not be exceeded more than once in 1,000 years. This flood has actually occurred once in the 60 years of record, hence the only safe conclusion is that such a flood need not be expected at frequent intervals although even a greater one may occur in any year.

253. **Are Floods Increasing in Intensity and Duration?**—Much of the United States has been settled less than a century and in many

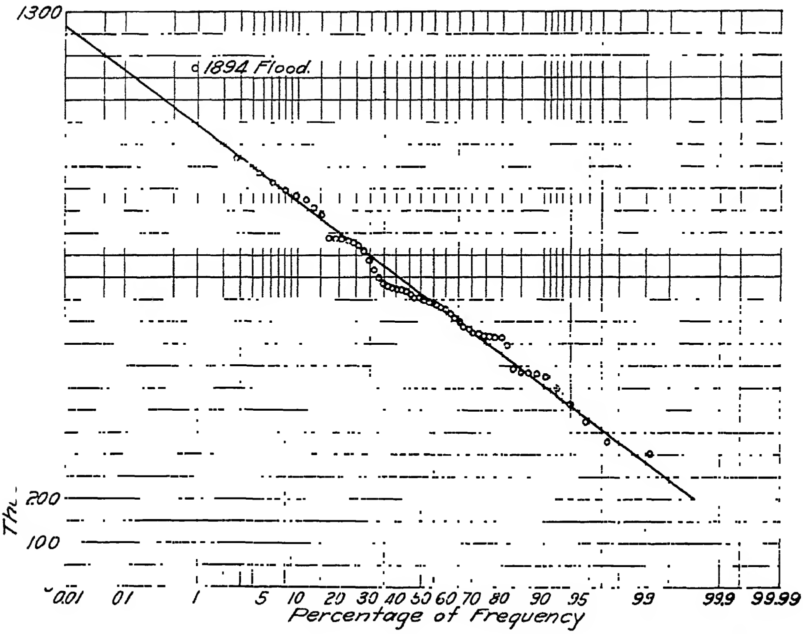


Fig. 335.—Probabilities of Flood Flows on the Columbia River. After L. F. Harza.

cases the maximum flood that must occasionally be expected has not occurred since the present communities have become important. In other cases serious losses of life and property have occurred and as the years pass and importance of the communities increases, more serious losses are to be expected. The occasional great flood which only rarely swept over the level area of the flood plain did no noticeable damage until man attempted to appropriate these areas for his own use, and hence the occurrence of these floods passed almost unnoticed and unrecorded. When, however, these occasional exceptional floods occur on thickly settled flood plains the loss becomes great and unprecedented.

On account of these losses and the fact that they have never been experienced previously in the affected region claims are made that

floods are increasing in frequency and in height or volume due to the changes wrought by man in the settlement of the country.

The foresters and others interested in reforestation have endeavored to show that deforestation has resulted in increased floods and reduced low water conditions. Engineers in general, however, are of the opinion that deforestation and cultivation have produced no radical changes of the kind indicated.

In general it may be stated that the time of observation in the country has been too brief to determine in an entirely satisfactory manner whether or not there has been any considerable change in flood height. The information available indicates no great changes except those due to channel restrictions. In the case of the longest records available the information is not wholly reliable for, while the gage readings are continuous, it is apparent that the datum or zero of the gage may have been sometimes altered either by accident or design. The high flood of 1805 preceding the great flood of 1913 in the Miami Valley, and the records of the floods of the Rhine at Emmerich and especially the records of floods in the Seine at Paris all serve to indicate the occurrence of great floods but show no evidence of any material change in flood heights.

In many cases flood heights have increased due to the restriction of the channel by levees built to prevent overflow or by encroachments due to the filling in of low lands for building sites. The general flood heights on the lower Mississippi River have been raised in this manner by the construction of the extensive levee system along that river. The flood elevation at Memphis, Tennessee, has been thus increased by eight or ten feet. Fig. 336 shows the maximum high waters on various rivers of the United States. For the earlier years only maximum floods are shown, authentic records of which were preserved on account of their unusual character. For the later years annual high water elevations are available. These records show no radical changes in flood heights but indicate that occasional floods which greatly exceed the ordinary annual high water flow must be expected. Such extreme floods apparently occur once in fifty or one hundred years, although there is no reason to believe that they may not follow each other at much shorter periods. On the other hand, the longer experience on European rivers seems to indicate that periods of several years of excessive floods or of unusual low water frequently occur.

Probably the most conclusive evidence that there has been no material changes in extreme flood conditions is furnished by the investigation of

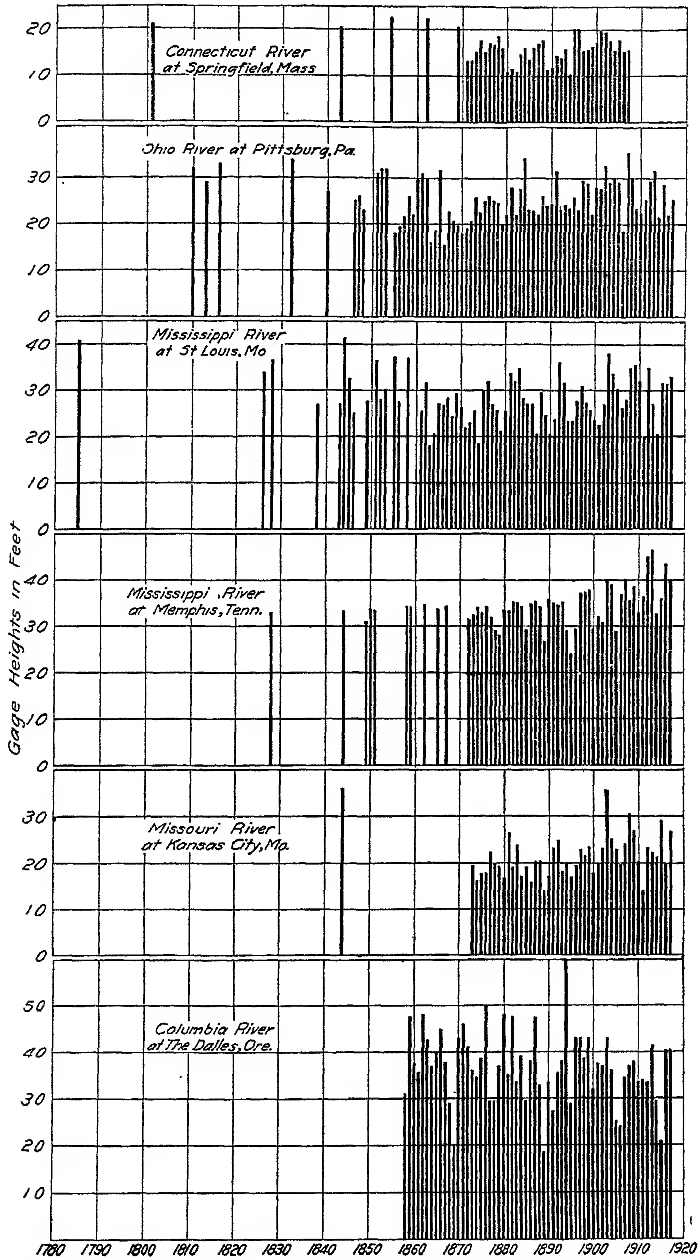


Fig. 336.—Maximum Annual Gage Heights on Various Rivers of the United States.

M. Ernst Landa, Chief of the Hydrographic Bureau of the Austrian Government, in his investigations of the floods of the Danube,[19] with special reference to the floods of 1897 and 1899. M. Landa reviews the records of the excessive floods of the years 1012, 1118, 1126, 1193, 1194, 1195, 1210, 1234, 1235, 1236, 1275, 1280, 1281, 1284, 1285, 1295, 1312, 1315, 1316, 1317, 1340, 1342, 1359, 1402, 1404, 1405, 1406, 1407, 1408, 1409, 1434, 1437, 1445, 1464, 1465, 1491, 1499, 1501, 1508, 1520, 1527, etc. The floods of later years while described in greater detail in the original report are not mentioned in detail in the translation.

Mr. Landa's conclusions are as follows:

"To conclude from this chronological record of the Danube floods that these catastrophes have increased in number, extent and frequency in modern times would be as absurd as to maintain the opposite. The history of the past tells of floods which were not subordinate to those of the present in any of the above particulars. Two conclusions clearly follow from this retrospect:

"(a) The floods of 1897 and 1899 were not abnormal or unusual phenomena in the history of the river.

"(b) Regulation works have had absolutely no influence in increasing the heights of floods."

General Chittenden in commenting on this report says:

"The number of floods cited by the author is about 125. Many of them were accompanied by ice gorges which render close comparison with other floods by means of discharge or gage data rather uncertain. A noteworthy feature of the record is the occurrence of flood years in groups. In nearly the entire period, high flood years were bunched together, showing that precipitation moves in cycles."[19]

254. **The Effect of Storage on Flood Heights.**—It has previously been noted that the effect of ground or surface storage is to reduce materially the flood heights (Sec. 203, p. 456), and that high floods may be entirely obviated by artificial control (Fig. 274, p. 464) where such control is physically possible and financially practicable. From this consideration it becomes evident that the relative floods on even adjacent streams may vary greatly with the natural storage on their drainage areas. Mr. W. E. Fuller has considered the effects of storage on flood conditions under certain assumed conditions which though necessarily hypothetical are instructive (Fig. 337). Even where little natural storage may exist in the ground or in lakes and swamps, the

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[19] Forests and floods, Extracts from an Austrian Report on Floods on the Danube, H. M. Chittenden, Eng. News, Vol. 60, p. 467, 1908.

temporary storage produced by the overflow of river valleys during floods will modify to a considerable extent the flood heights and discharge at points farther down the stream.

In many alluvial valleys the normal heights of extreme floods cause an extensive overflow by which large quantities of water are temporarily impounded in the bottom lands until the receding floods allow them to drain back into the streams. The amount of such storage in the lower Mississippi valley prior to the construction of the levee system was enormous (see Sec. 245).

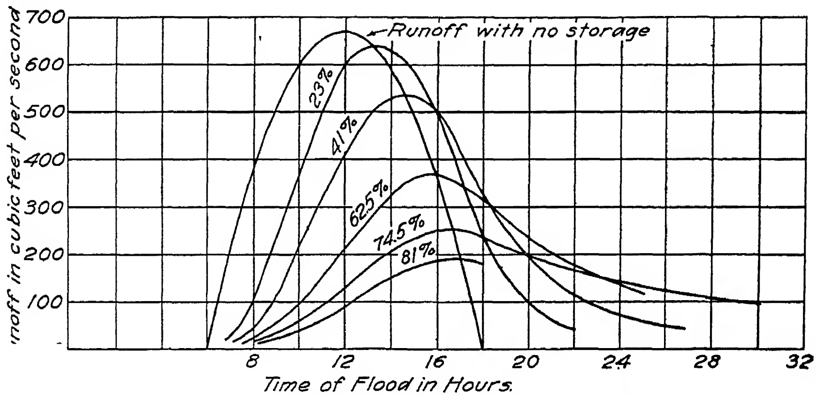

FIG. 337.—Effect of Storage on Flood Height. After W. E. Fuller.

The flood plain of the lower Mississippi River has been built up by the deposition of sediment adjacent to the river channel and the bottom lands slope back from the channel to a considerably lower elevation than the river bank and are drained by various tributaries which enter the main river many miles below. The section of the valley from Memphis westward to Crowley's Ridge is shown in Fig. 338, from which it will be noted that the floods prior to the construction of the levees could overflow a section about 37 miles in width. By the construction of levees the floods are now retained in the river channel and the consequent flood heights at Memphis have been increased eight or ten feet above the elevation to which they rose in times prior to the construction of these levees, as will be noted by reference to Fig. 336.

When channel improvements are undertaken to reduce or prevent overflow in a river valley, the storage which has been hitherto effective in reducing flood heights at such times is removed or reduced and higher floods will consequently be experienced at points farther down the

stream. This is an important matter which is frequently neglected in plans for levees and channel improvements.

In considering plans for the flood protection of the Miami valley, a study* was undertaken to determine the maximum discharge that would have occurred at Dayton and Hamilton in the 1913 flood if the river channel had been improved to a capacity sufficient to permit the water to flow directly down the channel without overflowing the flood plain.

The total quantity of water stored above Hamilton at the time of the peak of the flood was 568,000 acre feet or about .3 of the total rainfall which produced the flood, and equivalent to a depth of 2.9 inches over the entire drainage area.

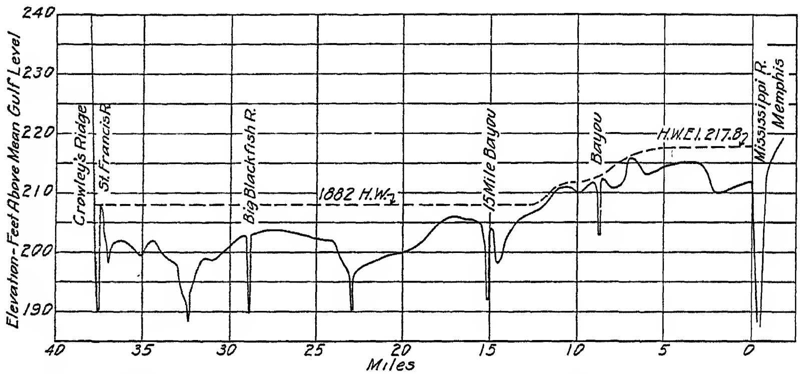

FIG. 338.—Profile of the Alluvial Flood Plain of the Mississippi River from Memphis, Tenn., to Crowley's Ridge, Ark., along the C. R. I. & P. Ry. After Mississippi River Commission.

With the channels enlarged to confine the entire flood flow to the river channel, no storage on the flood plain would obtain but the channel storage would be increased due to the necessary increase in their capacity; hence the net amount of storage elimination would be the difference between the valley storage which could practically be eliminated, and the increased channel storage. The valley storage extended far up the tributaries and not all of it would be affected by improvements of the main river channel, although the depression of the flood plain in the main channel would draw down the flood plain of the tributaries to a considerable extent. In this study the assumption was made after

*This example (see Fig. 339, page 578), is taken from an unpublished study of the effects of eliminating storage in the Miami Valley by Assistant Engineer, K. B. Bragg and is here published by permission of Mr. A. E. Morgan, Chief Engineer.

due consideration, that the reduction in valley storage would equal 451,000 acre feet or about 80% of the total valley storage. The excess channel storage which would be created by the necessary channel improvements was estimated at 194,000 acre feet. This amount deduced from the 451,000 acre feet assumed to be eliminated from the overflow of the valley would leave a net reduction to be removed by the channel of 257,000 acre feet.

The Miami River began to overflow and the valley storage above Hamilton became appreciable when the flow at Hamilton reached a discharge of about 40,000 second feet, and reached its maximum about 34 hours thereafter. As all of the valley storage was empounded within this time, that part of it which would be eliminated would necessarily have to pass Hamilton by the time the flood peak occurred. To determine, therefore, the resulting maximum flow of water which would occur at Hamilton, provided valley storage were eliminated, this additional quantity of water must be added to the Hamilton hydrograph between the hours when the overflow began and the time at which the flood peak occurred. As the flood actually occurred, this valley storage which would be eliminated by channel improvements was stored above Hamilton at the time of the peak and passed through with the recession of the flood wave. If the storage were eliminated this amount of water would be added to the advancing flood wave or to the front part of the hydrograph and would be withdrawn from the receding wave or be subtracted from the latter part of the hydrograph between the discharge limits of the maximum and the time that the falling flood had again reached a discharge of 40,000 second feet, thus keeping the total flow between the overflow limits the same. This calculation can be made most accurately by graphical methods. The general shape of the revised hydrograph was determined from a knowledge of the characteristics of inflow and outflow curves from retarding basins, and the exact dimensions were determined by planimeter by making the additions to and the deductions from the hydrograph equal to each other and to the amount of storage eliminated (Fig. 339 A).

From the investigation the maximum flow at Hamilton under the improved channel conditions was found to be 500,000 second feet or about 150,000 second feet above the flow that actually occurred.

A similar study was also made of the increased flow at Dayton by the elimination of the valley storage above that city which showed an increased flow at that place of about 80,000 second feet (Fig. 339 B).

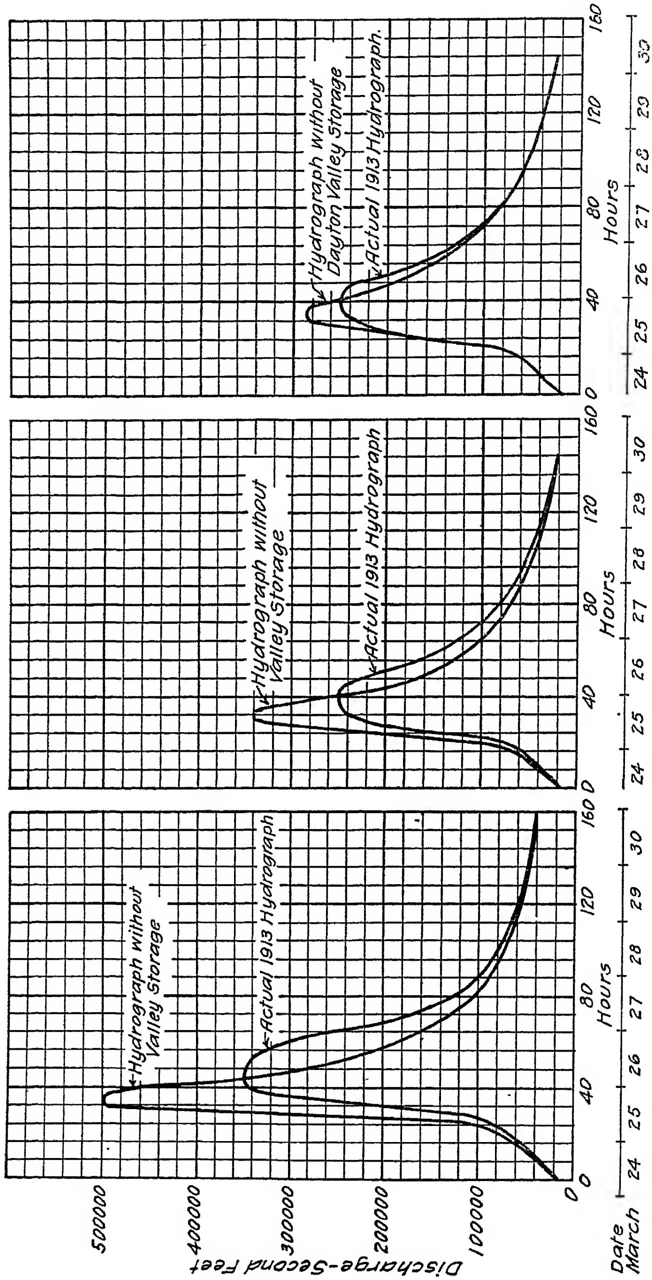

FIG. 339.—Comparative Hydrographs of Actual Floods on the Miami River, and the Modification which would have been produced by the Elimination of Valley Storage.

A study was also made to determine what the additional flow would be through Dayton if channel improvements were confined to Dayton only, and assuming that the flood plain above the City would not be depressed, thus eliminating only the valley storage within the city itself.

The storage in the City of Dayton amounted to 83,700 acre feet and the total flow occasioned by its elimination was estimated at 285,000 second feet or 35,000 second feet greater than the total flood flow during the flood of 1913 (Fig. 339 C).

There are two important points to be noted in connection with the matter discussed in this section:

1st. That the maximum unit flood discharge will decrease with the increase in valley storage and that in considering the probable maximum flood discharge to be anticipated in any stream at the present or in the future, the conditions which now prevail and which may prevail in the future must be given due weight.

2d. That when levees and other works necessary to reclaim low lands or to prevent the overflow of cities or agricultural lands are constructed, they will if they restrict the channels and reduce overflow, accentuate flood heights and increase flood flows; and it becomes important that such effects be anticipated and cared for in the design of such improvements.

255. The Intensity of the Flood Runoff of Streams.—In the determination of the maximum flood flows to be provided for in the construction of hydraulic works or in determining the intensity of runoff which may occur at times of maximum flood, it is necessary that the local conditions be investigated in each particular case. Consideration must be given to every factor which influences the amount of runoff and no unit flood should be adopted as a basis of design without a thorough investigation of its applicability to the existing conditions. In general, the flood runoff data from the local stream and from other streams that are fairly comparative should be correlated and studied. The intensity, duration and distribution of rainfalls producing great floods on the stream in question and on other streams over which the same storm centers pass should be platted and studied, and the maximum storm that should be expected at seasons of the year when conditions favorable to high runoff obtain, should be determined as closely as practicable. The adoption of a unit discharge as determined from the practice at other places or from runoff formulas, based on unknown conditions or on conditions quite foreign to the locality under investigation, is never excusable although such practices and formulas may

TABLE 59.

Runoff Formulas for Streams.

Authority	Formula	Original Purpose and Reference
1. Fanning ...	$Q = 200\,M^{5/6}$	New England Streams Treatise on Water Power Engineering
2. Dickens ...	$Q = 500\,M^{3/4}$	Central Provinces India Indian Professional Papers
3. Ganguillet .	$Q = \dfrac{1{,}421\,M}{3.11 + \sqrt{M}}$	Swiss streams Proc. Inst. C. E., Vol. 71, 1883
4. Italian	$Q = \dfrac{1{,}819\,M}{0.311 + \sqrt{M}}$	Streams of North Italy Report on Barge Canal, 1901
5. Kuichling ..	$Q = \left(\dfrac{44{,}000}{M + 170} + 20\right) M$	Mohawk River occasional floods
6. Kuichling ..	$Q = \left(\dfrac{127{,}000}{M + 370} + 7.4\right) M$	Mohawk River rare floods Report on Barge Canal, 1901
7. Murphy and Others	$Q = \left(\dfrac{46{,}790}{M + 320} + 15\right) M$	General U. S. G. S. Paper No. 147
8. Fuller	$Q_{av} = C_1 M^{0.8}$ $Q = Q_{av}\,(1 + 0.8 \log T)$ $Q_{max} = Q\,(1 + 2\,M^{-0.3})$	General Trans. Am. Soc. C. E., Vol. 77, 1914
9. Burge	$Q = 1300 \dfrac{M}{L^{2/3}}$	Madras Railway, India Jackson Hydraulic Manual, 1875
10. Craig	$Q = 440\,C_2\,W \text{ hyp. log } \dfrac{8L^2}{W}$	Proc. Inst. C. E., Vol. 80, 1885

Nomenclature

Q = Maximum (24 hour average) flood in cubic feet per second
Q_{max} = Maximum Flow at Flood Peak in cubic per second
Q_{av} = Average Yearly Flood in cubic feet per second
M = Drainage Area in square miles
L = Length of Drainage Area in Miles to point of discharge
T = Number of years in the period considered
W = Width of Drainage Area in Miles
C_1 = Coefficient which should vary with each stream
C_2 = VP (from 0.68 to 1.95 for small mountain districts)
V = Velocity of approach to point of Discharge
P = Coefficient (.12 to .18)

serve as a rough guide in the investigation. It must always be remembered that each problem is independent and is not subject to a general solution.

After a thorough study of the question and due consideration of the best information available, a flood flow may be adopted for the purpose in question, using a factor of safety as great as the importance of the local conditions will warrant.

A large number of empirical formulas which attempt to approximate the flood runoff from a given area have been devised. Such formulas have usually been developed for certain streams or for certain areas in which the streams are believed to possess common characteristics. They have seldom been intended for general application to all streams

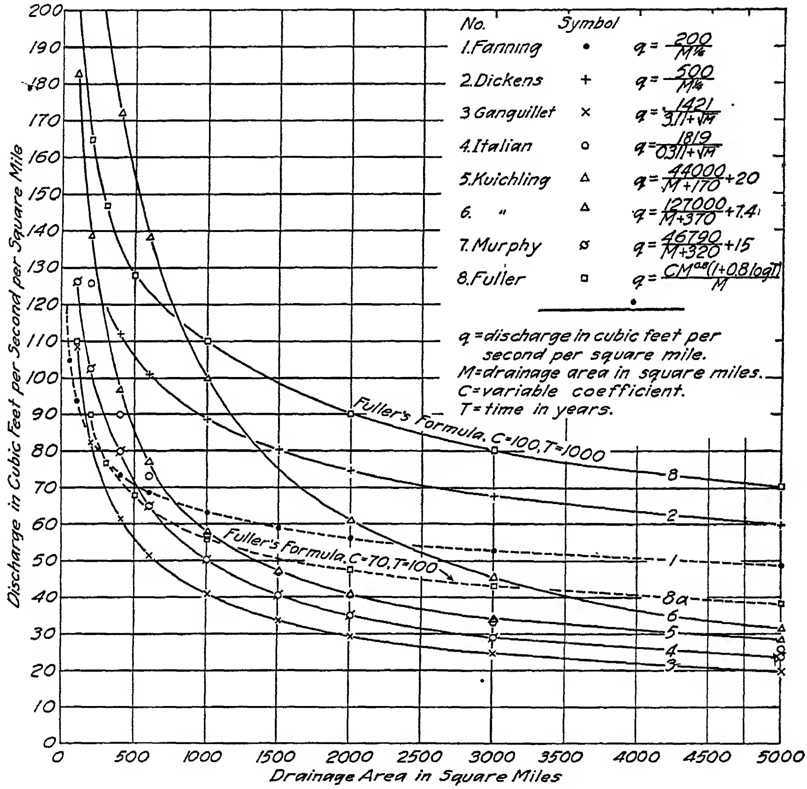

FIG. 340.—A Comparison of Various Runoff Formulas.

or to streams having widely different characteristics, and when so intended attempt to accomplish the end by means of radical changes in their variable coefficients. Unfortunately the limited applicability of such formulas is not always understood and consequently they often have been selected without proper caution and used with disastrous effects. Some of these formulas are shown in Table 59 and graphically in Fig. 340. Each one is based on more or less extended observations and is applicable only when used under conditions similar to those for which it was devised. Very few of these formulas take into account the

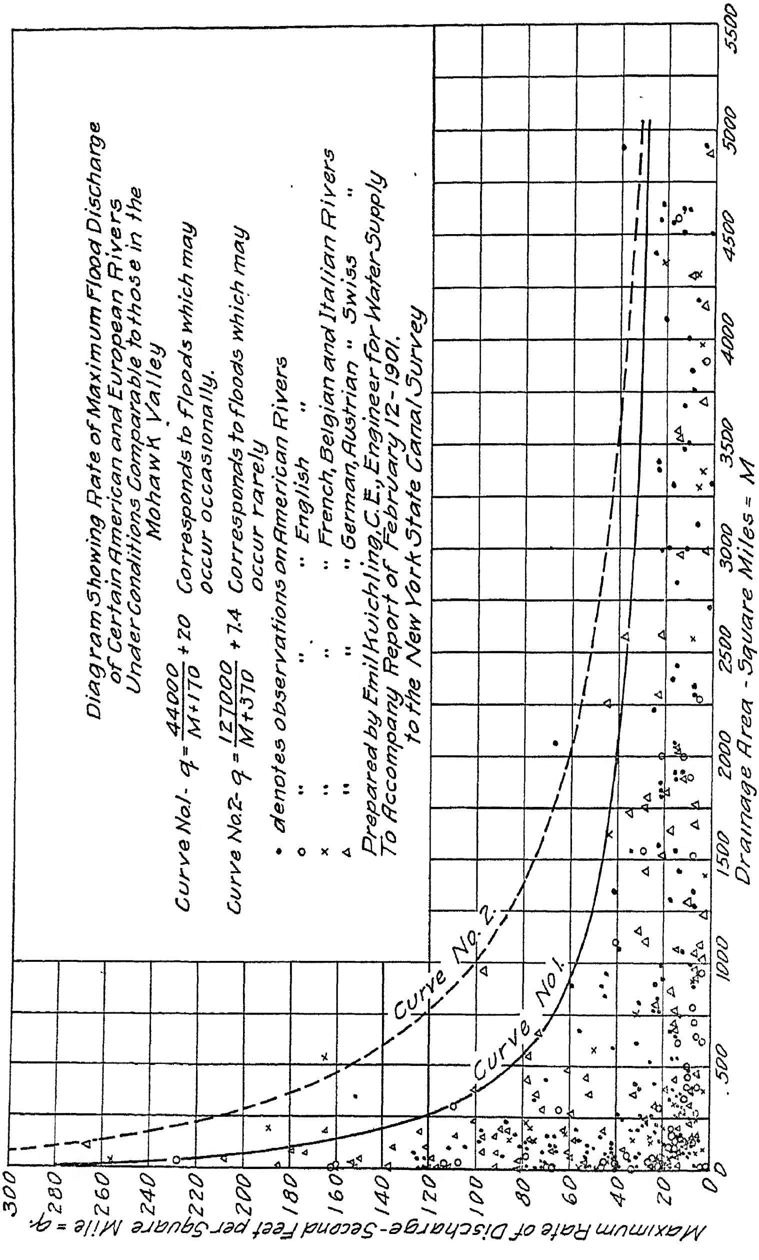

FIG. 341.—Kuichlings Curves of Occasional and Rare Floods, with Data upon which they were based.

great number of conditions that modify the results. For this reason most of such formulas are of little use except for the purpose of rough approximation. Fig. 341 shows graphically the formulas of Kuichling[20] for flood flows under conditions comparable to those in the Mohawk Valley, New York, and indicate the data upon which such formulas are based.

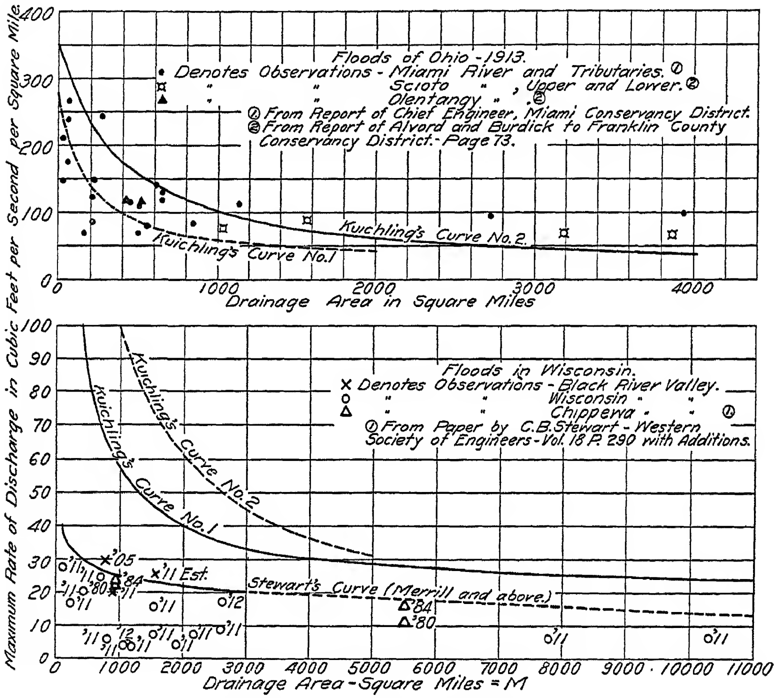

FIG. 342.—Various Conditions to which Kuichling's Curves do not apply.

A study of the data platted on this diagram and used as a basis for these formulas shows that they consist of most of the records of maximum runoff of the streams of the world that were available at the time the formulas were devised, and that the conditions of runoff of many of these streams are in no sense fairly comparable with those conditions in the Mohawk Valley. It would therefore seem that the formulas were not intended to be limited to the Mohawk Valley but were for general application, and for such purposes they, together with other similar formulas, have come to be more or less commonly

[20] Report on New York Barge Canal, 1901.

employed. That a general use of such formulas is entirely unwarranted will be seen from the following illustration of their applicability to two areas in northern United States where conditions might easily be supposed to be somewhat similar to those in the Mohawk Valley, much more nearly comparable than many of the areas from which runoff data were actually used as the bases of these formulas.

Fig. 342 A is a comparison of the flood flows of 1913 on the Miami and Scioto Rivers and their tributaries with Kuichling's curves and shows that if flood protection works on those rivers had been based upon the formula for "rare floods" they would have been entirely inadequate. Fig. 342 B is a comparison of the maximum flood flows on certain Wisconsin Rivers which shows that even Kuichling's formula for "occasional floods" would probably give results too large and require works too expensive for that stream. This diagram also shows a discharge curve recommended by Mr: C. B. Stewart for application to the Wisconsin River at and above Merrill, Wisconsin.

It may be remarked that even within the State of Wisconsin the maximum floods so far experienced differ greatly on different streams. The maximum floods on the Wisconsin River are about double those on the Rock and Fox Rivers while those on the Black River are about fifty per cent. greater than those on the Wisconsin. It therefore seems evident that no general solution of the flood problem is possible but that each problem should be considered in detail and should be based on data that are truly comparable.*

256. Runoff From City Areas.—In calculating the runoff from city areas somewhat different forms of expressions which are also applicable to the runoff of streams are used. In these formulas (Table 60) the rate of rainfall (see Secs. 124–128) and the slope of

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*For records of flood flows see:

Report on the Barge Canal, State of New York, 1901, p. 844

Hydrology of the State of New York, New York State Museum Bul. 85, 1905.

Geological Survey of New Jersey, Vol. III, Water Supplies, 1904.

Reports of Floods, U. S. Geological Survey, Water Supply Papers 88, 92, 96, 147, 162 and 334.

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Flood Flows, W. E. Fuller, Trans. Am. Soc. C. E., Vol. 77, 1914, Tables 12 to 27 and Table 37 in discussion of this paper by Mr. Kuichling.

River Stages, Vols. 1 to 15, U. S. Weather Bureau.

the drainage area are considered as factors, and certain coefficients are introduced which should be modified by the local conditions of surface, storage, topography, etc. The determination of the coefficient for local use requires a study of the results which have obtained in other places where similar conditions have prevailed and a comparison of such conditions with those of the locality for which similar or modified results are desired. For the conservative application of these formulas to local problems the engineer should refer to their more extended discussion in the references given.

257. **Flood Runoff From Drainage Districts.**—The flood runoff from the low flat lands of drainage districts is from the nature of the area drained much less intense than from the normal drainage areas of streams. The drainage investigations of the U. S. Department of Agriculture furnish much pertinent data concerning actual runoff observations in different parts of the country.[21] In drainage work it is generally recognized that the amount of water to be removed from a district will increase with the amount and intensity of the rainfall, and few attempts have been made to devise formulas of general application. In each case it is usual to select or devise a formula that fits the conditions. (Table 61.)

In the Mississippi Valley the annual rainfall and in general the intensity of rain storms increase from the source to the mouth of the river, and the runoff of drainage districts will likewise increase. Mr. C. G. Elliot[22] has suggested a formula, No. 1, Table 61, for calculating runoff to be provided for drainage ditches in swamps and other wet lands of the Upper Mississippi Valley where the soils are absorptive and easily drained. Such a formula should not be used however except for rough approximations until it is checked for local conditions. As the rainfall increases the discharge will increase, so in the swamp land of Missouri and the Lower Mississippi Valley higher estimates of runoff are found necessary for satisfactory drainage work.

In the preliminary work of the Drainage Investigations in Northeastern Arkansas,[23] the discharge from the low flat alluvial lands were

21 See Publications of Office of Experimental Station "Drainage Investigations," U. S. Department of Agriculture.

22 Engineering for Land Drainage, C. G. Elliot, John Wiley & Sons, New York, 1912.

23 A Preliminary Report on the St. Francis Valley Drainage Project in Northeastern Arkansas, A. E. Morgan, Circular 86, Office Experimental Station, p. 20, 1919.

TABLE 60.

Runoff Formulas for Metropolitan Districts and Streams.

Nomenclature

A = Area drained in acres.
S = Ave. slope in feet per 1000.
i = Max. intensity of rainfall, inches per hour.
Q = Discharge, cu. ft. per sec.
d = Diam. of circular sewer, inches.
C = Coefficient.
N = Length of sewer in which fall is 1 ft.
a, b, c = Empirical constants.
f = Duration of heaviest rain which will cause Q to become an absolute maximum.
P = Proportion of impervious surface.

Name	Year	Published	Formula	Values of Coefficients	Reference No.
1. Hawksley	1857	Report of Commission Metropolitan Drainage (London 1857)	$\log d = \frac{3 \log A + \log N + 6.8}{10}$		1 2 3
			$Q = ACi \sqrt[4]{\frac{S}{Ai}}$	C = 0.7, i = 1.0	4
2. Burkli-Ziegler.	1880	"The Greatest Discharge of Municipal Sewers" (Zurich 1880)	$Q = ACi \sqrt[4]{\frac{S}{A}}$	C = 0.7 to 0.9 i = 1.0 to 3.0	1 2 3 4
3. Adams	1880	"Sewers and Drains for Populous Districts" Col. J. W. Adams (New York 1880)	$Q = ACi \sqrt[6]{\frac{S^{1/2}}{Ai}}$	C = 1.837 i = 1.0	1 2 3 4
4. McMath	1887	Trans. A. S. C. E., Vol. 16, p. 183 (St. Louis)	$Q = ACi \sqrt[5]{\frac{S}{A}}$	C = 0.75 For St. Louis i = 2.75 C = 0.1 to 0.8 General i = 1.0 to 2.75	1 2 4
5. Hering	1889	Rept. Baltimore Sewerage Commission 1897 Deduced by Gregory from Hering's Report of 1889 New York	$Q = CiA^{.85} S^{0.27}$ $Q = CiA^{.833} S^{0.27}$	Ci = 1.02 to 1.64 1.02 suburban dist. 1.64 metropolitan dist.	1 2

TABLE 60—Continued.

Runoff Formulas for Metropolitan Districts and Streams.

Name	Year	Published	Formula	Values of Coefficients	Reference No.
6. Parmley	1898	Jour. Assoc. Eng. Soc., Vol. 20, p. 204, The Walworth Sewer of Cleveland, O.	$Q = ACi \sqrt[6]{\frac{S^{3/2}}{A}}$	$C = 0$ to 1.0 $i = 4.0$ for Cleveland to provide for most violent storm and to allow for prevailing direction of storm	1 2 5
7. Kuichling	1889	Trans. A. S. C. E., Vol. 20, p. 1	$Q = ACi$ $C = at$ $i = b - ct$	$b = 2.10$ Rochester exp. $c = 0.0205$ $a = \frac{P}{t}$ $t =$ time for absolute maximum $= \frac{b}{2c}$	4
8. Gregory	1907	Trans. A. S. C. E., Vol. 58, p. 458	$Q = ACi \frac{S^{0.186}}{A^{0.14}}$	$Ci = 2.8$ for impervious surface	1 2

References.

No.

1. American Sewerage Practice, Vol. 1, Metcalf and Eddy, 1914, p. 235.
2. Rainfall and Runoff in Storm Water Sewerage, C. E. Gregory, A. S. C. E., Vol. 58, p. 458, 1907
3. Rainfall and its Runoff into Sewers, S. A. Greeley, Jour. W. S. E., Apr. 1 1913.
4. Relation between Rainfall and Discharge of Sewers in Populous Districts, E. Kuichling, Trans. A. S. C. E., Vol. 20, p. 1.
5. The Walworth Sewer, Cleveland, O., W. C. Parmley, Trans, A. S. C. E., Vol. 55, p. 345, 1905.

calculated from Formula No. 2, Table 61. For other conditions in the same district this formula would not give adequate results.

"For the more rolling and less sandy land in the east part of Mississippi County the estimated runoff was increased 50 per cent. For the clay soils east of Crowleys Ridge the quantities obtained by the use of the formula were doubled in making estimates, and for the slopes of

TABLE 61.

Runoff from Swamps and Wet Lands.

Author	Formula	Application
1. C. G. Elliot	$q = \frac{20}{\sqrt{M}} + 3.63$	Upper Mississippi Valley[22] absorptive and easily drained soils
2. C. G. Elliot	$q = \frac{24}{\sqrt{M}} + 6$	Northwestern Arkansas[23]
3. Morgan Engineering Co.	$q = \frac{28.0}{\sqrt{M}} + 7.2$	Mississippi County, Ark.
4. Morgan Eng. Co...	$q = \frac{38.0}{\sqrt{M}} + 8.0$	Cache River Drainage District
5. S. H. McCrory and others	$q = \frac{35}{\sqrt[6]{M}}$	Cypress Creek Drainage District, Arkansas.[24]
6.	$q = \frac{90}{\sqrt{M}} + 10$	Tentative formula for certain Louisiana districts. (No considerable storage in bayous and ditches)
7.	$q = \frac{3400}{M + 50} + 5$	Tentative formula for certain districts in Florida Everglades

q = sec. ft. per sq. mi., M = area in sq. mi.

Crowleys Ridge three times the quantities determined by the formula were taken as the probable flood runoff."[23]

It should also be noted that in the actual development of some of these swamp lands it was found that Equation No. 2 would not give sufficiently high unit discharge for satisfactory drainage and formulas Nos. 3 and 4, Table 61, were the basis used by the Morgan Engineering Company of Memphis, Tennessee, in their design of the necessary works.

In the report upon the Cypress Creek Drainage District in Desha and Chicot Counties, Arkansas,[24] Formula No. 5, Table 61 was used which gives materially higher unit runoff for that district; and in Louisiana,

[24] Bulletin 198, Professional Papers U. S. Dept. of Agriculture, 1915.

where still more extreme rainfall conditions are encountered, the runoff must be estimated on a still higher basis and Formula No. 6, Table 61, was used as a tentative basis for the investigation of certain districts in this area. Most of the Louisiana districts require the installation of pumping plants, and in many cases more or less extensive bayous are included within the levied areas. These bayous in connection with the ditch system often afford extensive storage which when properly utilized reduces the size of the pumping plants which need to be installed to keep the land free from water.

In certain investigations in the Florida Everglades, where rainfalls are still more intense than in Louisiana, Formula No. 7 of Table 61, was tentatively adopted as a basis for drainage estimates.

The conclusions to be drawn from an examination of these formulas are that such expressions must be chosen or devised for each particular district and then represent only their author's conclusions based on more or less pertinent data concerning local conditions and local runoff.

In designing ditches even in the same drainage district or in districts closely adjoining, it is not always safe to use the same expression for runoff as an area with clay soil will discharge much more water than a district with sandy soil, and a different basis must therefore be used for the design of the ditches when the condition of soil so requires.

258. **Flood Flows of Small Streams for Determining the Capacities of Railway Culverts.**—There are comparatively few records of the flood flows from small areas the drainage from which must be provided for by railway culverts, yet these flows must be anticipated in the construction of numerous structures in railway lines. The runoff formulas used by a few railroads in determining the area of waterways, together with statements of the confidence placed in the computed results, are given in the following extracts from the committee report on "Roadway," published in the American Railway Engineering and Maintenance of Way Association, Vol. 10, Part 2, 1909, to which the engineer should refer for a more extended discussion.

The Pittsburg and Lake Erie Railroad (J. A. Atwood, Chief Engineer) uses Burkli-Ziegler and McMath formulas, obtaining the area by survey or from government topographic sheets. Maximum rainfall at 3 inches and $C = 0.3$. The Burkli-Ziegler formula is used only when $\frac{S}{A}$ exceeds unity.

The Chicago, Rock Island and Pacific Railroad (John C. Beye, locating engineer) determines the area, slope and surface conditions of basin

by actual survey where practicable, otherwise by maps. The formula used in Talbot's

$$x = CA^{3/4}$$

x = area of waterway opening in square feet.
For flat area $C = 1/3$
For hilly area $C = 2/3$
For mountainous area $C = 1$ or more

The culvert is made 50 to 100 per cent. larger than the formula calls for, when possible.

The Chicago, Burlington and Quincy Railroad (T. E. Calvert, Chief Engineer) obtains drainage areas by actual survey or from reliable maps. For areas less than 1000 acres, the McMath formula is used:

$$Q = 2.0625 \sqrt[5]{15 A^4}$$

For areas greater than 1000 acres

$$Q = \frac{3000 M}{3 + 2 \sqrt{M}}$$

The results are relied upon unless recorded high water marks indicate an extra large waterway is necessary.

The Missouri Pacific Railway (W. C. Curd, Chief Engineer) determines areas and surface conditions by survey or from reliable maps. No one formula is relied upon but the conclusions are checked up in all possible ways. The Talbot, McMath or Burkli-Ziegler formula may receive the greatest confidence in determining the runoff, depending upon the data. Some excess is always provided, depending upon the size and local conditions.

The Missouri, Kansas and Texas Railway (S. B. Fisher, Chief Engineer) uses Talbot's formula with the value of C as follows:

Steep slopes	$C = 1.1$
Medium slopes	$C = 0.85$
Flat slopes	$C = 0.60$

The areas and design are changed as appears to be made necessary by local conditions.

The Baltimore and Ohio Railway (J. B. Jenkins, Assistant Engineer) obtains traces of former floods, fall and cross section of stream by survey. This result is compared with Talbot's formula with a factor (C) of 4 or 5 for mountainous, $2/3$ for hilly, $1/2$ for medium, $1/3$ for rolling and $1/5$ for flat ground, the factor being increased in regions of heavy rainfall for shape of basin favorable to rapid runoff, etc. The opening is usually made 20% greater than would be required by the greatest known flood except when the flood was very exceptional.

Practically all the railroads depend somewhat upon the results of computations from some one or more of the many formulas for runoff, but in practically no cases are these accepted as a final estimate. Consideration is properly given to the many factors which influence the runoff but which make the preparation of any formula extremely complicated if not impossible.

259. The Derivation or Selection of Formulas for Flood Flows.—From the previous discussion it should be evident that runoff formulas should never be used until their applicability to the conditions of the problem is determined from authentic data derived from areas having similar characteristics and after the most complete practicable investigation. The formula should then be selected or derived to fit the data and conditions with perhaps a reasonable factor of safety. The use of such formulas therefore is mainly to adjust conditions or to proportion works designed to conserve or control flood flows from an area different in extent but similar in character to those on which the formula is based.

For example, formula 2 in Section 257 was determined from the assumption that for an area of 9 square miles the flood discharge would equal 40 second feet per square mile and that for an area of 100 square miles the flood discharge would equal 19 second feet per square mile. Substituting these expressions in the general formula (Type 1) the value of x and y can be determined and the corresponding discharge for areas of other sizes calculated. If the resulting equation when platted does not fit the general condition, a formula of different form may be derived from other general equations such as Type 2 or Type 3.

Type 1 $$q = \frac{\quad}{\sqrt{M}} + y$$

Type $$q = \frac{\quad}{M + y} + z$$

Type 3 $$q = \frac{x}{y\sqrt{M}}$$

The student will find it instructive to practice devising such formulas. For example, a formula of Type 1 may be derived to fit the conditions:

Area Square Miles	Discharge Second Feet per Square Mile
200	12
50	17

and a formula of Type 2 may be derived to exceed the records of the flood flow of the Black River (Fig. 340) by 10% or 25%. Such practice will be useful in showing the method of derivation of such expressions and in giving a better idea of their true value and of the danger in their careless selection and use.

260. **The Economics of Flood Protection Work.**—In general the maximum flood which may be expected from a given drainage area is indeterminate. There are no floods of record so great that it is reasonable to conclude that there can be no greater. It is always possible that a rainfall of greater intensity, wider distribution and longer duration may sometime occur or that other conditions may prevail which may create more serious flood conditions than have yet occurred. On the other hand, from the data previously considered there is evidence that the combination of conditions which produces maximum floods is very rare, perhaps once in 500 to 1000 years; that floods of a lower magnitude will occur once in 100 to 200 years; and that lesser floods of various degrees will appear in various shorter periods, not with any regularity in occurrence but as an average of past conditions. If the engineer attempts to design flood protection works for the greatest flood he can imagine, most of such works will be entirely impracticable.

In the consideration of floods and works necessary to mitigate or prevent their undesirable consequences, the engineer must constantly keep in mind economic conditions. It is apparent that no works of any kind are warranted unless the resulting betterments exceed in value the cost of the improvements, and the parties interested are able to raise the funds necessary to meet the expense which will be incurred. Where such works are undertaken by a community the law requires that the benefits which will be derived therefrom must exceed their costs and that the cost must not be excessive.

In the construction of agricultural drainage works it is often inexpedient to provide for the maximum flood that may occur even every five years. The effect of the temporary flooding of agricultural land if for brief periods only is not serious. The interest and maintenance costs on works of a capacity suitable for extreme conditions would make their construction impracticable and it is better to face occasional losses or damages of crops than to attempt such expenditures. For example, Formula 3, Table 61, was used by the Morgan Engineering Company for drainage work in Mississippi County, Arkansas, as the best which the conditions warranted at the time of construction. As was expected, the lower lands are flooded to some extent about once in three

years and undoubtedly as the lands increase in value the ditches will be enlarged so that they will overflow only at rare intervals, corresponding more nearly with the conditions expressed by Formula 4 of Table 61.

It should be noted in this connection that the damage caused by the overflow of levees is much greater than if no levees were in existence, and that in most cases economic levee construction should be based upon a considerably higher rate of runoff than need be used as a basis of canal or ditch design. The probable damages which will be entailed in consequence of flooding due to extraordinary storms must be kept in mind in all such cases but the physical and financial conditions of each project will usually establish the limits of expenditures beyond which it is impracticable to go.

In most cases of storm water sewer design the size of the sewers can rarely be made adequate to provide for the maximum storm which may possibly occur, and a balance must be fixed between the cost of the works required to protect the district against floods of a certain magnitude and the damages which may result from storms of greater magnitude. Commonly the flood which will probably occur once in ten, fifteen, twenty-five or fifty years is used as a basis of design according to the importance of the interests involved and the comparative costs of construction. It may be shown in many cases that the extra cost of more extensive work if set aside at interest would accumulate a sinking fund in excess of the damage which would be entailed by the exceptional flood in which case extra investments are unwarranted.

In the recent construction of a small water power dam in Central Wisconsin it was thought desirable to about double the spillway capacity which had been available and sufficient in case of the old dam which had stood for perhaps forty years. It was recognized, however, that even the increased capacity of the new dam would be insufficient to pass floods which would be occasioned by storms of the intensity of that of July 24, 1912 (Table 27, page 248) at Merrill, Wisconsin, or that of June 10, 1905, at Bonaparte in Southeastern Iowa (see Table 27). In view of the remote possibilities of the occurrence of such storms it was necessary to take the chances of such an occurrence for otherwise the project would have to have been definitely abandoned on account of the great expense involved.

In more important works where life may be sacrificed by failure and where great financial interests are involved, greater factors of safety must be used. In the design of the works of the Miami Conservancy

District provisions have been made to protect the District against a flood about 40% in excess of the flood of March, 1913 (Fig. 343 A), which is believed to be the maximum flood which can reasonably be expected, and the works under construction are designed to sustain without injury even a greater flood.

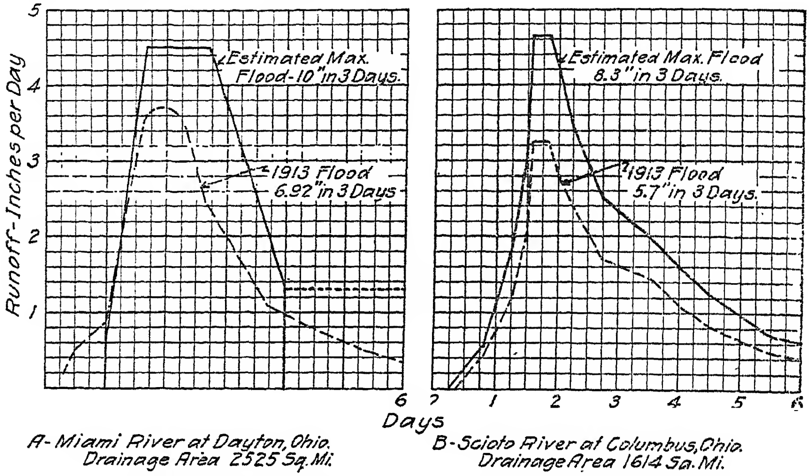

FIG. 343.—Comparison of Actual Floods of March, 1913, with ideal Maximums for which Flood Protection Works are to be designed.[7, 8]

The proposed works for the flood protection of Columbus, Ohio, also provide for a flood of considerably greater magnitude than the maximum recorded flood which has occurred at the place (Fig. 343 B).

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CHAPTER XX

THE APPLICATION OF HYDROLOGY

261. **Fundamental Consideration.**—Hydrology and all other applied sciences must be regarded as a means to an end and not as an end in themselves. The only reason for any engineering construction or for any engineering project is that as a result sufficient benefit will accrue to some individual or to some group of individuals to warrânt the expense involved. As a consequence of this truth, in the application of the principles of hydrology to the work of the engineer, all conclusions must be modified by the various factors which influence each particular project for the utilization or control of water.

In general, the factors to be considered in addition to or concurrent with the principles of Hydrology are as follows:

I. *Available Funds:* Sufficient funds must be available to meet the cost of the project.

(a) Amount will modify possibilities, extent and character of entire development.

(b) Source, taxation, special assessment, bonds, stocks, voluntary contributions.

The possibility of securing funds by taxation and assessment depends on the laws of state, and the amount which may be raised by this means depends on the assessed valuation of the property to be taxed for the improvement. The possibility of financing by sale of stocks and bonds depends on the value of the property involved in the project, the laws under which they may legally be issued and the income which may be earned by the property or the returns which may accrue from legal assessments.

II. *Purpose Served:* The project must serve some useful purpose.

(a) Public service (water supply, water power and navigation).
(b) Maintenance or improvement of sanitary conditions and public health (sewerage, drainage).

(c) Betterment of physical conditions and increase in real estate values (irrigation and drainage).
(d) Protection of life and property (flood protection).

III. *Physical Conditions:* The conditions which obtain should be favorable to moderate cost, safe construction, reasonable maintenance and free from serious contingencies.
(a) Methods, materials, equipment and machinery available for the proposed development.
(b) Comparative security of structures and methods available.
(c) Comparative economy of various types of structures and methods.
(d) Contingencies of construction, maintenance and operation.

IV. *Economic Considerations:* A comparison of costs and benefits. The benefits from the project must equal or exceed the costs.
(a) Costs.
Capital Costs: Real estate, Construction, Interest and Development expense.
Operation, maintenance and depreciation expense.
(b) Benefits: Income from project, Increase in values (of real estate), Improvement in health and living conditions and Protection of life and property.

When benefits can be estimated either as annual dividends or as increase in real estate values, a comparison of such benefits with the costs and contingencies involved, will furnish a fair criterion as to the advisability of the project. The maintenance or improvement to health and the protection of life and property cannot always be given a monetary value, but the desirability is easily established and the financial limitations are often quite obvious.

The study of each of the factors above outlined requires technical training, knowledge and experience. The details are so numerous that only a few items can be discussed in order to give the student the idea of how various factors must influence hydrological deductions.

262. Applied Hydrology.—In general engineering work in which hydrology plays an important part may be divided into:

I. Works for the utilization of waters; and
II. Works for the control of waters.

In most projects, however, both utilization and control may be important.

I. Projects for the utilization of waters may be divided into:

A. Private and public water supplies for domestic and manufacturing purposes.
B. Irrigation of agricultural land.
C. Water power.
D. Internal navigation.

II. Projects for the control of water may include:
a. The drainage and sewerage of cities.
b. The drainage of agricultural lands.
c. Works for the flood protection of cities, communities and lands.

In the following sections each of the principal classes of hydraulic work to which the principles of hydrology most directly apply is briefly considered, some of the main factors which may modify hydrological conclusions are briefly discussed, and an outline is given which constitutes an analysis of the main factors which should be considered in all projects of the class discussed. The table of literature that follows the chapter gives a few of the principal books and articles in which these matters are discussed at greater length.

263. **Water Supply.**—Water is primarily more essential than food, for distress will be entailed earlier from a scarcity or absence of water than of food. Both water and food must be available however if life is to be maintained in any locality. Every home, farm or community of any kind must be provided with water if it is to be even temporarily established. The securing of a water supply may therefore be considered as the most important object of applied hydrology.

In the application of hydrological principles to the problem of the development of a water supply two main questions are involved which are in turn greatly modified in their application by other variable conditions. These main questions are quantity and quality of the available supplies.

The question of quantity while no more important than that of quality, is ordinarily the first to receive consideration, for in every problem of water supply it is of primary importance that there shall be a sufficient supply for the purposes under consideration or the purpose must be modified if the quantity needed cannot be obtained. In determining quantity both present and future conditions must receive consideration (see Sec. 210, p. 473).

A common error in the selection of sources of water supply has been the consideration of only the most obvious source and the neglect or elimination of other sources less obvious but possibly of greater relative importance. It is uniformly desirable that every source which will

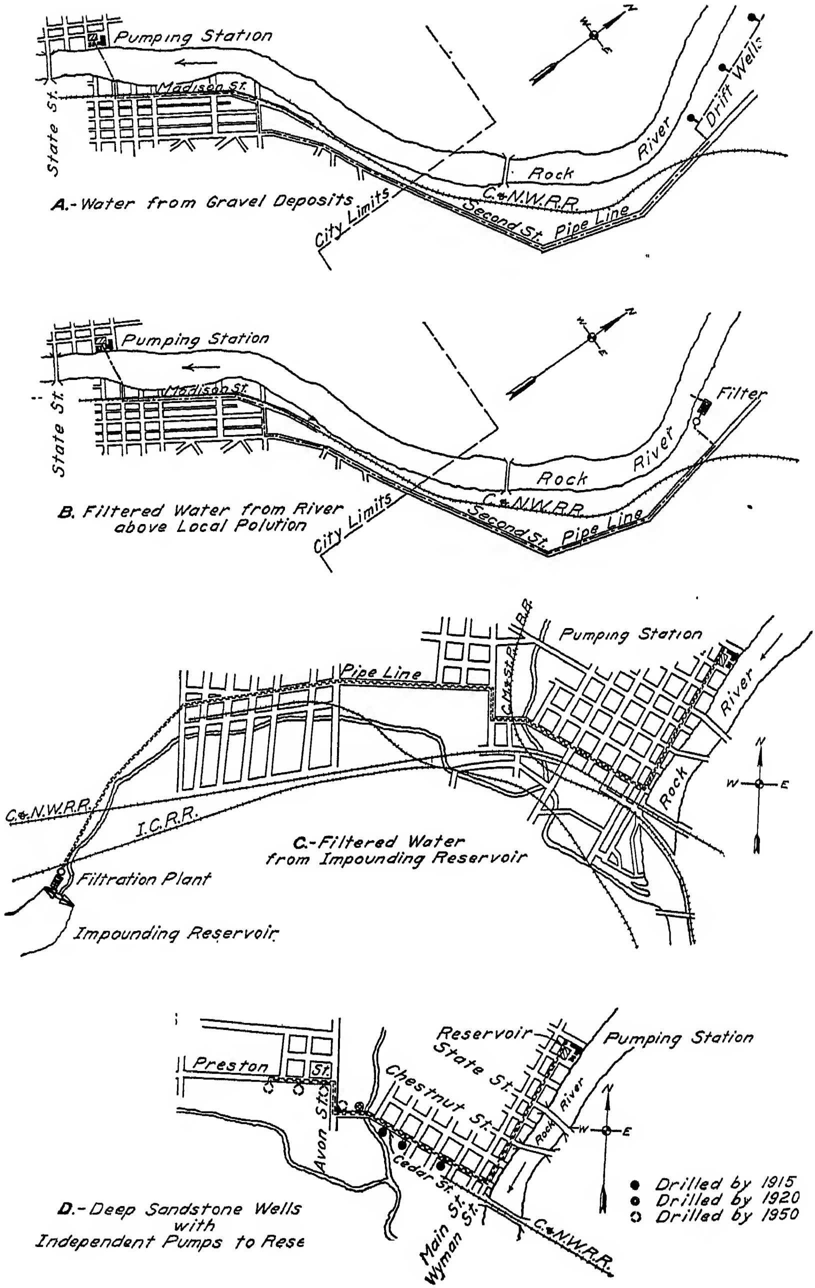

FIG. 344.—Possible Sources of Water Supply for Rockford, Illinois,

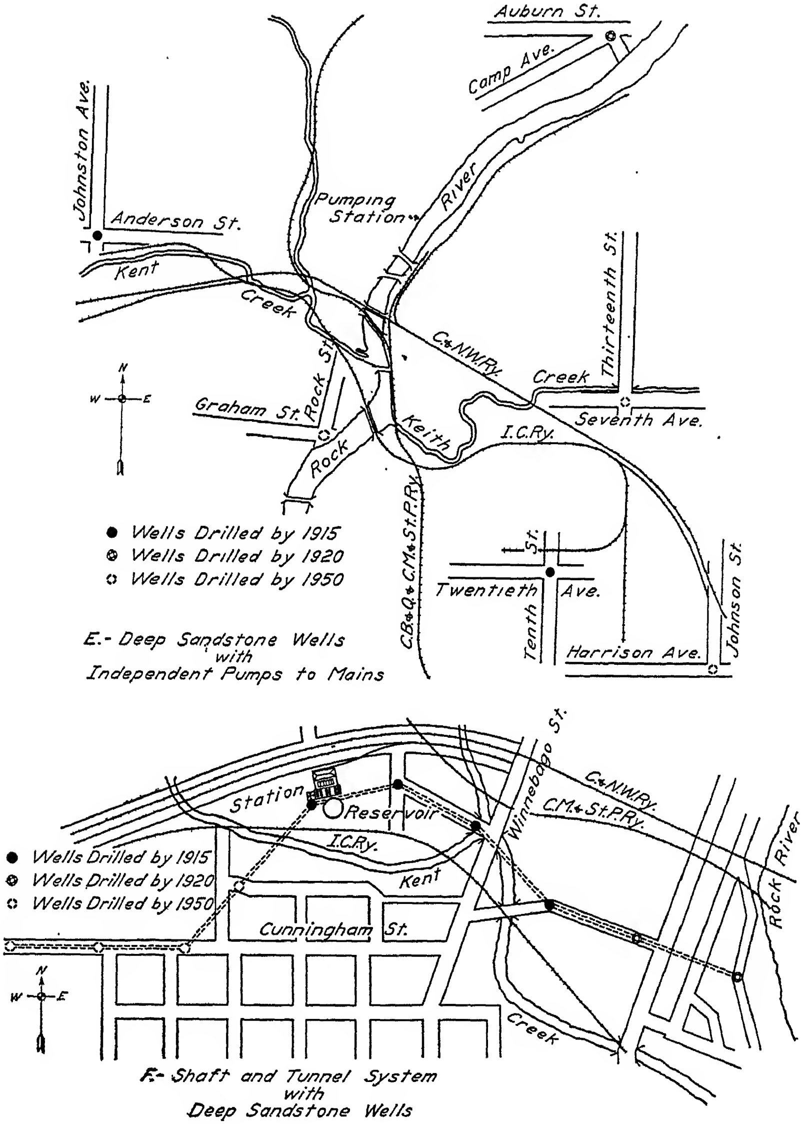

FIG. 345.—Possible Sources of Water Supply for Rockford, Illinois.

yield a sufficient quantity and which seems reasonably feasible of development should be considered. In considering such various sources it is necessary to take into account not only the quantity obtainable from each but also the methods by which each can be developed and

made available and the expense involved in the same. This will necessarily include the consideration of such processes as may be necessary for improving the quality to make each source unobjectionable as a water supply for the use and purposes contemplated. It is quite obvious that in many cases sources which are possible will be shown on brief investigation to be impracticable on account of the expense or other factors involved. Such sources can then be eliminated from further consideration and only those sources which are fairly comparative or unquestionably desirable may be reserved for final consideration and analysis.

264. **Comparison of Sources of Water Supply.**—I. *Sources.*—As an example of the various sources and methods of development which are sometimes available, the main possible schemes for a water supply for Rockford, Illinois, are shown in Figs. 344 and 345. These schemes include four different sources, viz.:

1. Gravel water from the drift (Fig. 344A).
2. River water filtered (Fig. 344B).
3. Spring and creek water filtered (Fig. 344C).
4. Artesian water from the Potsdam and St. Peter sandstone, developed by three different methods:
   a. By low lift pumps into a reservoir (Fig. 344D).
   b. By high lift pumps directly into the water mains (Fig. 345E).
   c. By a shaft and tunnel system pumping from the wells either into a reservoir by low lift pumps or directly into the water mains by high lift pumps (Fig. 345F).

II. *Quality.* In the comparison of these sources and methods of supply, quality must be considered and it is to be noted that in the Rockford problem the filtration of either the creek (Fig. 344C) or river (Fig. 344B) water was contemplated. The artesian water possesses the advantage of organic purity but is harder than the creek or river water. The gravel water is also open to the objection of still greater hardness. In some cases where the softening of the water is essential or desirable, the cost of softening should also be contemplated in such a comparison.

III. *Equipment.* In the comparison of sources and methods of development, the type of equipment which is or may be made available for the development is an important factor which modifies:

1st. The reliability of the development.
2d. The capital cost of development.

3d. The cost of operation and maintenance.

It is obvious that these factors cannot be discussed in detail in a text on hydrology, but it seems pertinent to point out that if a dependable source can be obtained of satisfactory quality and of a sufficient height to be supplied by gravity the cost of operation will be less, and there are many other advantages over a supply where machinery is necessary to produce the pressure at which the water must be delivered. On the other hand, the cost of development of the gravity supply, on account of distance from the source, may render the project too expensive for consideration, and the adoption of a pumping project may be necessary for financial reasons. Again, in pumping projects the relative reliability of the machinery to be used, the expense of operation, and the contingencies of maintenance may greatly modify the value of one source as compared with another.

In the same way, the necessity of clarification, filtration or softening plants involves complications, contingencies and expenses which will materially modify the choice of a source. The selection of a source may also be greatly influenced by the necessity of storage and the sites available for reservoirs, each of which will affect the expense of development.

The above comments will be sufficient to point out a few of the various modifying influences which must be considered in the selection of a source of public water supply in addition to the principles of hydrology which have been previously discussed. In general, the principal factors to be considered in every water supply problem are outlined in the following section.

265. Outline of Factors for Public Water Supply Investigation.—

I. Purpose.

1. Uses of and necessities for water supply: A domestic, B manufacturing, C sanitary, D agriculture, E fire protection, F ornamental.

II. Supply.

2. Sources of water supply: A rain water, B rivers, C lakes, D ground waters.
3. Character of supply: A quantity, B quality.
4. Quantity: A population, past and prospective, B variation in demand, seasonal, hourly, fire, C regulation by storage.
5. Quality: A improvement of quality: (sedimentation, coagulation and subsidence, aeration, filtration, hardening, softening, sterilization).
6. Method of supply: A gravity, B pumping.
7. Character of service: A constant, B intermittent, C high pressure, D low pressure.

III. System.

8. Pumping plants: A primary and secondary pumping, B sources of power (water, coal, gas, oil, wind, electricity) C accessories (buildings, boilers, producers, motors, pumps, governors, relief valves).
9. Aqueducts, tunnels and conduits for collection and transmission (concrete, masonry, wood, iron).
10. Pipes, distribution: A cast iron, B wrought iron, C steel (riveted, spiral riveted, welded), D wood, E lead.
11. Accessories: A hydrants (gate or valve), nozzles (single, double, steamer, B valves and valve boxes, C air valves, D relief valves, E service meters.
12. Appurtenances: A filters and works for clarification, B reservoirs and works for storage, C elevated tanks and standpipe.
13. Design and Construction (present and future requirements), A water supply system, B pumping system, C power house, D reservoirs and basins, E filters and methods of clarification, etc., F transmission and distribution systems (pipes, hydrants, valves, services, meters, plumbing).

IV. Cost Estimates.

14. Land and water rights: A rights of way, B condemnation, C damages.
15. Promotion, administration, engineering, supervision, legal expenses.
16. Time of construction and interest during construction.
17. Cost of structures: works and overhead costs.
18. Expense of developing business.
19. Cost of financing: Discounts, interest and sinking fund.
20. Maintenance, depreciation, operation, contingencies.
21. Estimated returns: gross and net profits from projects.

V. Management.

22. Private or municipal ownership: A supervision, B office, C field, D plant, E books, F records, G rules and regulations.

VI. Financial.

23. Financing: A development expense, B operation, C maintenance, D depreciation, E valuation.

VII. Final Conclusion.

24. Comparative data, general discussion, recommendations.

266. **Irrigation.**—I. *Application.*—In arid regions agriculture can be carried on only by means of irrigation, and as the sources of water supply in such regions are from the nature of the regions very limited, the amount of land which can be made available for agriculture by irrigation is also very limited and will become more and more important and valuable as the populations of such regions increase.

In semi-arid regions crop failures in the absence of irrigation are frequent and irrigation is usually essential to profitable agriculture. When

irrigation is impracticable, dry farming methods, which are largely methods for the conservation of the soil water, are sometimes found feasible. In thickly populated humid regions intensive agriculture can be carried on only by means of irrigation, and in the suburban gardens surrounding large cities irrigation methods established at considerable expense are amply warranted.

II. *Extent.*—The extent to which irrigation has been developed in the United States and the character of the various enterprises are indicated by the 1910 Report of the U. S. Census Bureau (Table 62) which however includes only the large projects of the Western States.

TABLE 62.

Extent and Character of Irrigation Enterprises in the United States in 1910.

Character of Enterprise	Acreage Irrigated in 1909	Acreage Capable of Irrigation in 1910	Acreage Included in Projects
Carey Act	288,553	1,089,677	2,573,874
U. S. Reclamation Service	395,646	786,190	1,973,016
U. S. Indian Reservations	172,912	376,576	879,068
Irrigation Districts	528,642	800,451	1,581,465
Co-Operative Enterprises	4,643,539	6,191,577	8,830,197
Individual and Partnership Enterprises	6,257,387	7,666,110	10,153,545
Commercial Enterprises	1,451,806	2,424,116	5,119,977
	13,738,485	19,334,697	31,111,142

An idea of the extent of work involved in the irrigation of this land can be gathered from Table 63 which gives the U. S. Census Summary of Irrigation Statistics for 1910.

TABLE 63.

Summary of Irrigation Statistics for the United States in 1910 (Not including areas devoted to growing rice) U. S. Census 1910.

Total Acreage Irrigated	13,738,485	acres
Total Acreage that could have been irrigated........	19,334,697	acres
Total Acreage Included in Projects	31,111,142	acres
Number of Irrigation Enterprises	54,700	acres
Length of Canals and Ditches	125,591	miles
Length of Main Canals and Ditches	87,529	miles
Length of Lateral Canals and Ditches	38,062	miles
Number of Reservoirs	6,812	miles
Capacity of Reservoirs	12,581,129	acre feet
Number of Flowing Wells	5,070	
Number of Pumped Wells	14,558	
Number of Pumping Plants	13,906	
Aggregate of Power used in Pumping	243,435	H. P.
Acreage Irrigated with Pumped Water	477,625	acres
Acreage Irrigated from Flowing Wells	144,400	acres
Aggregate Cost of Irrigation Enterprises	$307,866,369	
Average Cost per Acre	$15.92	
Average Cost of Operation and Maintenance per year	1.07	per acre

Fig. 346 shows the location of the various irrigation enterprises of the U. S. Reclamation Service. Up to June 30, 1916, there were 1,405,452 irrigable acres on these projects 922,821 of which were irrigated during the preceding year, and there had been expended on these projects a total of $149,786,534. The value of the total crops raised on all of the reclamation projects in 1916 was $32,815,972. It

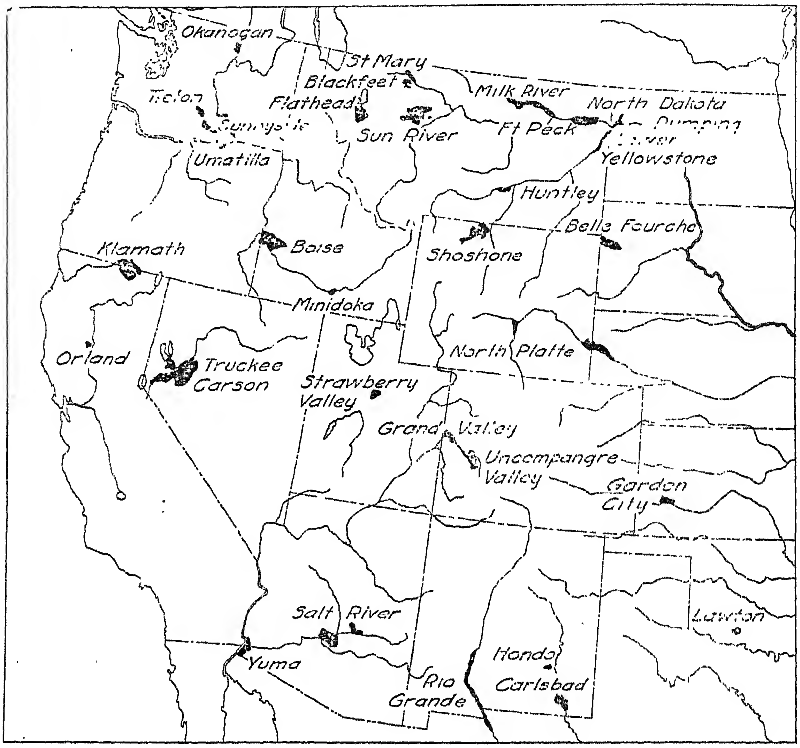

FIG. 346.—Principal Projects of the United States Reclamation Service.

was estimated by Secretary Lane, in his annual report for the year ending June 30, 1918, that there are 15,000,000 to 20,000,000 acres of arid land at present in the West for which water can be made available by proper conservation.

III. *Profit from Irrigation Developments.*—Properly planned irrigation enterprises have proved very profitable and have been of great value to promoters, irrigators and to the Nation. Suitable desert land which can be purchased under certain legal restrictions at low cost (sometimes as low as $1.25 per acre) becomes worth from $50 to $100

per acre and upward when successfully irrigated. The costs of irrigation work vary widely from as low as $5.00 per acre to $100 per acre, and more. The margin of profit between cost of land plus a low cost of development and the high values of the best irrigated farms seems to offer opportunities for high returns, and these opportunities have induced promoters to undertake many ill advised, ill designed and unfortunate ventures until at the present time (1919) irrigation projects and irrigation securities are looked upon with suspicion by investors.

IV. *Causes of Irrigation Failures.*—Irrigation failures have resulted from many reasons but the most common cause of failure has been inadequate water supply. In general these failures have resulted from dishonesty and incompetency in management or from mistakes in judgment which are exhibited in some of the following ways:

Inadequate water supply
Inadequate plans
Poor construction
Excessive cost
Slow colonization
Excessive distance from market

It is apparent that an adequate supply of water for a suitable body of land is the primary requisite for successful irrigation, and most of the principles treated in the text covering the sources, qualities and quantities of water apply directly to this phase of the subject. An adequate and satisfactory supply is only one phase of the subject; the water must be properly conserved and transported to a suitable area to be irrigated. As the irrigation season is essentially the growing season, adequate storage is often essential to store the supply during the months when it is not needed so as to concentrate the supply and adapt it to the largest possible area during the irrigation season. This necessitates an adjustment between the supply and storage, the loss from evaporation, seepage, etc., and the demand. The study of these factors in relation to the supply of Salt River Project of the U. S. Reclamation Service is shown in Fig. 347 as applied to the flow at the Roosevelt Dam and its normal application to 161,111 acres of this project. Seepage must be considered not only as it affects the storage of water but also as it modifies the losses in transmitting it from reservoir to field. In many cases this transmission loss is enormous, and an adequate supply at the field to be irrigated frequently requires twice the required amount delivered from the reservoir. Soil and subsoil conditions are

therefore equally important to the water supply, for the soil must not only be suitable for irrigation purposes but the physical condition largely modifies the amount which must be supplied to meet the demand of the necessary losses in transmission and application. The topographical and physical conditions also affect the ultimate success for in many cases irrigation and especially over-irrigation results in a rise in the ground water and the deposit of alkali on the surface, and this necessitates the development of drainage or it results in the ruin of the land for agriculture, a consequence often apparently remote before land is irrigated but a consequence to be foreseen and considered in the intelligent development of plans for irrigation.

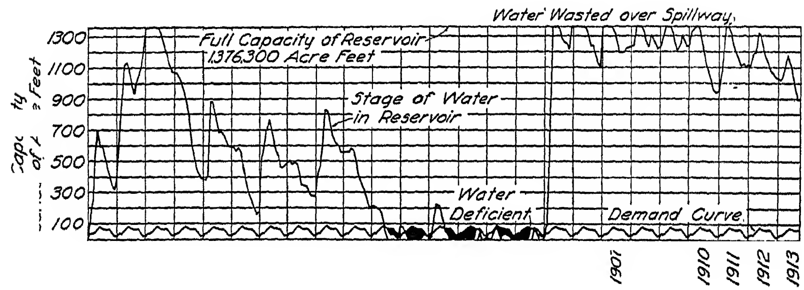

FIG. 347.—Analysis of Supply and Demand on the Flow of the Salt River as Modified by the Roosevelt Reservoir, when applied to 161,111 acres at the rate of 4.5 acre feet per acre.*

In connection with the development of irrigation and drainage projects a question of vital importance to financial success lies in the time which it takes to colonize the land and get it under successful cultivation. Colonization depends not only on an adequate supply of suitable lands economically developed but also on the demand for such land, proximity to a market and other factors which influence or control the probable profit to the settler who is to make the project his home and on whom the ultimate success of the project must depend.

Colonization is often a slow process and the profit which apparently should result in a great financial success may prove a financial failure on account of high carrying charges due to slow colonization. The

*See Salt River Project, Arizona, Limiting Area of Land, Dept. of Interior, U. S. Reclamation Projects, 1914, Washington, D. C.

average time to colonize various irrigation projects, based on experience up to 1910 as derived from the 1910 U. S. census returns, is shown in Fig. 348, and the results anticipated and realized from such slow development is illustrated in Table 64. This table illustrates the possibility of failure through delayed colonization of a project which

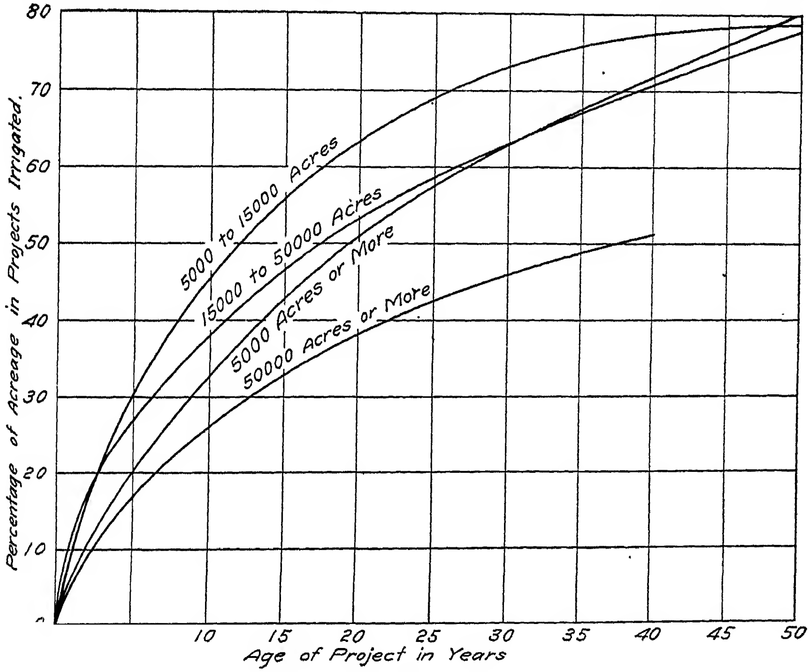

FIG. 348.—Diagram Showing Colonization of Average Irrigation Project According to U. S. Census Returns of 1910.*

might otherwise have been very profitable, and shows how factors other than those of hydrology or engineering must often influence and control a project.

267. Outline of Factors for Irrigation Investigations.—

I. Location of Project.

1. With regard to transportation and market, railroads, roads, nearest large cities and population, location of other projects, competition for sale of lands and sale of produce.

*See Eng. News, Vol. 76, p. 202.

TABLE 64.

Financial Computation for Irrigation Project During Colonization.

Hypotheses:
Area—1000,000 Acres,—Value, $100 per Acre, Total cost of $3,000,000 of Land and Construction $3,000,000.
Annual Cost $150,000, including administration, selling land, operation, maintenance, depreciation, etc.
Annual Maintenance charges collected—$2.00 per acre on all lands sold.

Year	Land Sales			Revenue			Expense			Total Investment	Total Residual Value of Lands at $100	Assets Company Holdings Minus Investment
	% for Year	% Total	Acres for Year	Land Sales at $100 Acre	Maintenance Charges $2.00 Acre	Total	Interest 6%	Operation etc.	Total			
	0	0			....	....	....	....	....	3,000,000	10,000,000	7,000,000
1	4	4	4,000	$400,000	....	$400,000	$180,000	$150,000	$330,000	2,930,000	9,600,000	6,670,000
2	4	8	4,000	400,000	$8,000	408,000	175,800	150,000	325,800	2,847,800	9,200,000	6,352,000
3	3	11	3,000	300,000	16,000	316,000	170,868	150,000	320,868	2,852,668	8,900,000	6,047,332
4	3	14	3,000	300,000	22,000	322,000	171,160	150,000	321,160	2,851,828	8,600,000	5,748,172
5	3	17	3,000	300,000	28,000	328,000	171,110	150,000	321,110	2,844,938	8,300,000	5,455,062
6	2	19	2,000	200,000	34,000	234,000	170,696	150,000	320,696	2,931,634	8,100,000	5,168,366
7	2	21	2,000	200,000	38,000	238,000	175,898	150,000	325,898	3,019,532	7,900,000	4,880,468
8	2	23	2,000	200,000	42,000	242,000	181,171	150,000	331,171	3,108,703	7,700,000	4,591,297
9	2	25	2,000	200,000	46,000	246,000	186,522	150,000	336,522	3,199,225	7,500,000	4,300,775
10	2	27	2,000	200,000	50,000	250,000	191,953	150,000	341,953	3,291,178	7,300,000	4,008,822
11	2	29	2,000	200,000	54,000	254,000	197,470	150,000	347,470	3,384,648	7,100,000	3,715,352
12	1	30	1,000	100,000	58,000	158,000	203,078	150,000	353,078	3,579,726	7,000,000	3,420,274
13	1	31	1,000	100,000	60,000	160,000	214,783	150,000	364,783	3,784,509	6,900,000	3,115,491
14	1	32	1,000	100,000	62,000	162,000	227,070	150,000	377,070	3,999,579	6,800,000	2,800,421
15	1	33	1,000	100,000	64,000	164,000	239,974	150,000	389,974	4,225,553	6,700,000	2,474,447
16	1	34	1,000	100,000	66,000	166,000	253,533	150,000	403,533	4,463,086	6,600,000	2,136,914
17	1	35	1,000	100,000	68,000	168,000	267,785	150,000	417,785	4,712,871	6,500,000	1,787,129
18	1	36	1,000	100,000	70,000	170,000	282,772	150,000	432,772	4,975,643	6,400,000	1,424,357
19	1	37	1,000	100,000	72,000	172,000	298,538	150,000	448,538	5,252,188	6,300,000	1,047,812
20	1	38	1,000	100,000	74,000	174,000	315,130	150,000	465,130	5,543,311	6,200,000	656,689
21	1	39	1,000	100,000	76,000	176,000	332,598	150,000	482,598	5,849,909	6,100,000	250,091
22	1	40	1,000	100,000	78,000	178,000	350,994	150,000	500,994	6,172,903	6,000,000	—172,903
23	1	41	1,000	100,000	80,000	180,000	370,374	150,000	520,374	6,513,277	5,900,000	—613,277
24	1	42	1,000	100,000	82,000	182,000	....	....	....	....	5,800,000	....
25	1	43	1,000	100,000	84,000	184,000	....	....	....	....	5,700,000	....

II. Physical Conditions.

2. Topography, geology, altitude, climate, temperature, rainfall (distribution through years, variation, extremes).

III. Land.

3. Quantity, availability, physical condition, nature.
4. Character of soil and subsoil: A alkali, B drainage, C seepage, D desirability or need of irrigation, E nature of vegetable growth, F clearing and grading, G ownership, H legal status, I value or cost.

IV. Surveys, Topographic and Hydrographic.

5. Land surveys: A canal and ditch location, B farm unit subdivision, C town sites, D telephone lines, E roadways, F railroads, etc.
6. Surface water: A flow of streams (records and gagings), B drainage area (character and topography), C rainfall (comparison of rainfall and flow with other longer records), D reservoirs.
7. Ground water: A depth to water surface, B nature of water bearing strata, C data.
8. Water requirements: A estimated quantity, B development, C works needed (intakes, galleries, reservoirs).
9. Pumping water: A methods, B character of fuel, C cost.
10. Character of water: A salts contained, B silt in flood and normal flow, C character and effect of silt.
11. Water laws: A legal rights, B prior appropriations, C adjudications, litigations.

V. Duty of Water.

12. Character of crops, water requirements of crops, irrigation season, load factor, soil conditions as affecting seepage and evaporation, drainage, methods of using, methods of distribution.
13. Losses in distribution, seepage losses, amount needed at source, amount needed at field, total water requirements.

VI. Development Works.

14. Diversion works: A dams (dimensions, foundations spillway, overfall, gates, apron).
15. Storage works: A reservoirs (geology, materials, seepage, cores, slopes, protection).
16. Controlling works: A head gates, B by pass, C overflow wasteways, D drops and chutes, E weirs, modules and meters.
17. Transmission works: A flumes, B tunnels, C canals, laterals and ditches (size, length, grade, character of soil, erosion, seepage, lining).
18. Transportation: A railroads, B roads, C bridges, culverts.
19. Pumping plants (condition, kind, class, power, fuel).
20. Drainage works: A ditches, B tile.
21. Auxiliary works, water power development (electric power, pumping).

VII. Labor and Materials.

22. Methods: A contract, B day labor.

23. Labor: A nationality, B availability, C cost, D teams.
24. Material: A sources, B distance, C cost at source, D cost f. o. b. railway, E cost of transportation.
25. Machinery and equipment required: A class, B source, C cost, D hauling.

VIII. Cost Estimates.

26. Land and water rights, cost of promotion, administration, engineering, legal advice, litigation, condemnation, damages, time of construction, interest during construction, cost of structures and works, overhead costs, cost of financing, sinking fund, payments, interest, colonization, estimated time required, cost of development, interest, maintenance, depreciation and operation, estimated return and new profits from venture.

IX. Final Conclusions.

27. Comparative data from other projects.
28. Recommendations.

FIG. 349.—Power House and Dam Abandoned Because Possible Power Output was not Sufficient to Pay for Operating.

268. **Water Power.**—The flow of streams is perennial. Coal, oil and gas are exhaustible. If the power of a flowing stream is developed for useful purposes, the country is richer, for something which otherwise would have been lost is saved and utilized; and in general such saving has also resulted in conserving an equivalent of fuel for the future which would have been lost. Water power is therefore an important application of hydrology which demands greater consideration than it has received as yet.

Agitation for so-called "conservation" has served to call attention to the desirability of the intelligent use of natural resources but has resulted in ill considered laws (1919) which have prevented development of water powers and resulted in a corresponding unnecessary use of exhaustible fuel resources.

Intelligently developed, water powers are not only profitable to their promoters but from the very fact of their success show that they fulfill a demand which results in profit to their customers and a saving in the exhaustible natural resources and a development of the country.

Water powers are not universally profitable. While the energy of running streams is a waste which a water power development is designed to prevent and to utilize, the expense of development is fre-

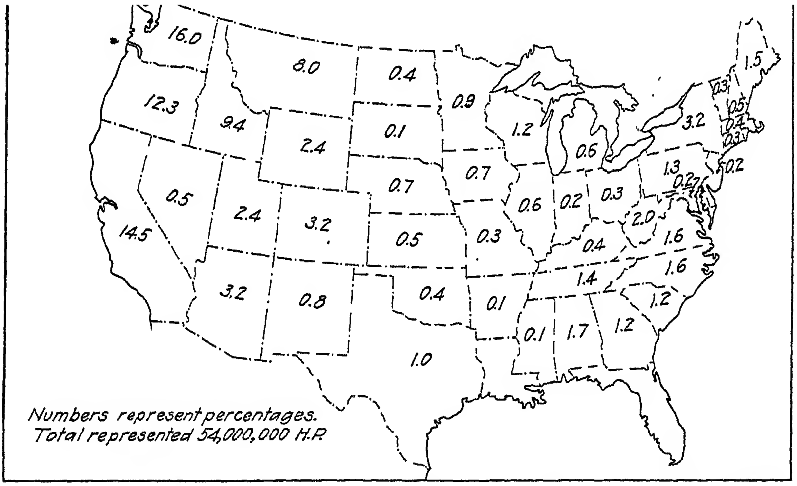

FIG. 350.—Percentage of Total Water Power in the United States Available in Each State.

quently so great as to be unwarranted by the economy effected by the saving. Fig. 349 shows a 50 foot dam with power house which, while built in good faith, was so ill advised that it did not pay to operate it even after it was constructed and the investment incurred. The machinery was removed through the opening in the power house wall and was installed on a larger stream. Many similar failures show the necessity of the consideration of all of the factors which when combined control the success of such projects.

In water power projects, water is an essential feature, and the regularity and quality of flow are important factors to investigate. (See Chapter XVI, p. 432). Head, however, is equally important and needs

full investigation as at times of flood, head is often reduced and is essentially eliminated in many low head plants.

The creation of head by the construction of dams requires an investigation of the geological conditions which are favorable or unfavorable to safe and economical storage of potential energies above a given site, and the intelligent construction of works to control and utilize the same.

Storage and pondage are also vital factors in water power utilization. In no case can water power be utilized at a continuous uniform load, and much power will be lost at times of low demands unless the water can be impounded at such times and utilized during the time of high demand. A comparative study of load factor, load demand, stream variation and storage possibilities is therefore often as important as quantitative studies of available stream flow.

The distribution of the approximate 54,000,000 horse power of water available in the United States is shown in Fig. 350. Of this only about 5,000,000 horse power were developed in 1912 so that water power projects affords a great field for engineering work.

269. Outline of Factors for Water Power Investigation.—

I. Market or Demand for Power (proximity, nature and extent of market).

1. Special use, particular industry, general, wholesale or retail sale of power, character of load, load factor, power factor, seasonal loading.

II. Physical Conditions.

2. Location: A topography, B geology, C climate, D rainfall (annual seasonal, variation), E temperatures (ice conditions), F frequency and character of storms (high winds, lightning) G earthquakes.

III. Hydrographic and Topographic Surveys.

3. Streamflow (annual, monthly, daily, gagings and records).
4. Flowage, storage and pondage (desirability, feasibility, effect).
5. Canals (location, excavation, construction, seepage, etc.).
6. Riparian lands, structure sites, railroads, transmission and telephone lines.
7. Head (amount and variation under high, low and medium flows).
8. Power (amount available, variations, amount desirable to develop, load factor).
9. Auxiliary power (necessity, probable amount, source, fuel cost, etc., effect on cost of delivered power).
10. Ultimate capacity and provisions for future growth of development.

IV. Water Power Laws.

11. Water rights, flowage rights, condemnation, privileges, damages, litigation.

V. Development.

12. Land: A site, B flowage, C rights of way, D roads, E bridges.
13. Dam: A foundations, B flood capacity, C spillway, D locks, E gates, F sluices, G fishways and logways.
14. Headrace: A capacities, B loss of head, C headgates, D canal, E tunnels, F soil, G erosion, H silt, I lining, J grade, K racks, L gates, M penstock (open, closed).
15. Power house and substations: A foundations, B type, (fireproof, wood, iron), C design (windows, doors, roof, floors, walls, galleries, rooms, stairways, heating, plumbing, water supply).
16. Tailrace: A capacity, B permanency, C loss of head, D soil and material, E lining, F silt.
17. Equipment: A turbines, B generators, C governors, D exciters, E switchboard, F lightning arresters, G transformers, H regulators, I oil purification, J gate operating machinery, K cranes.
18. Transmission: A line losses (distance, voltage, transformation, amount of power), B conductors (material, insulation, stringing and sagging, ground wires), C type (wood pole, steel pole, steel towers, durability, foundations, painting, galvanizing).

VI. Labor and Material.

19. Work done by contract or force account: A labor (nationality, availability), B teams, C construction plant, D cost.
20. Material: A sources, B transportation, C distance, D cost.
21. Machinery for construction purposes: A kind, B availability, C cost.

VII. Cost Estimate.

22. Water rights, real estate, flowage, rights of way, promotion, administration, engineering and legal expenses, time of construction, interest during construction, cost of construction and overhead, cost of financing, interest, discounts, sinking fund, payments, maintenance, depreciation, operation, taxes, cost of power, load, load factors, cost compared with power costs of plants used or which may be used in territory, cost of development of market, contingencies of construction, development and operation, damages, benefits, returns, profits.

VIII. Financing.

23. Common stock, preferred stock, bonds, securities, market, discount.

IX. General Conclusions.

24. Comparison with data from other developments, adequacy of works, conclusions, recommendations.

270. **Internal Navigation.**—In the early development of a country the navigation of the interior waters may be of the utmost importance as the only practicable method of transportation. With the growth of the country and the increase in importance of rapid communication and transportation, railways have largely displaced waterways in importance and in most countries waterways have assumed a second and very sub-

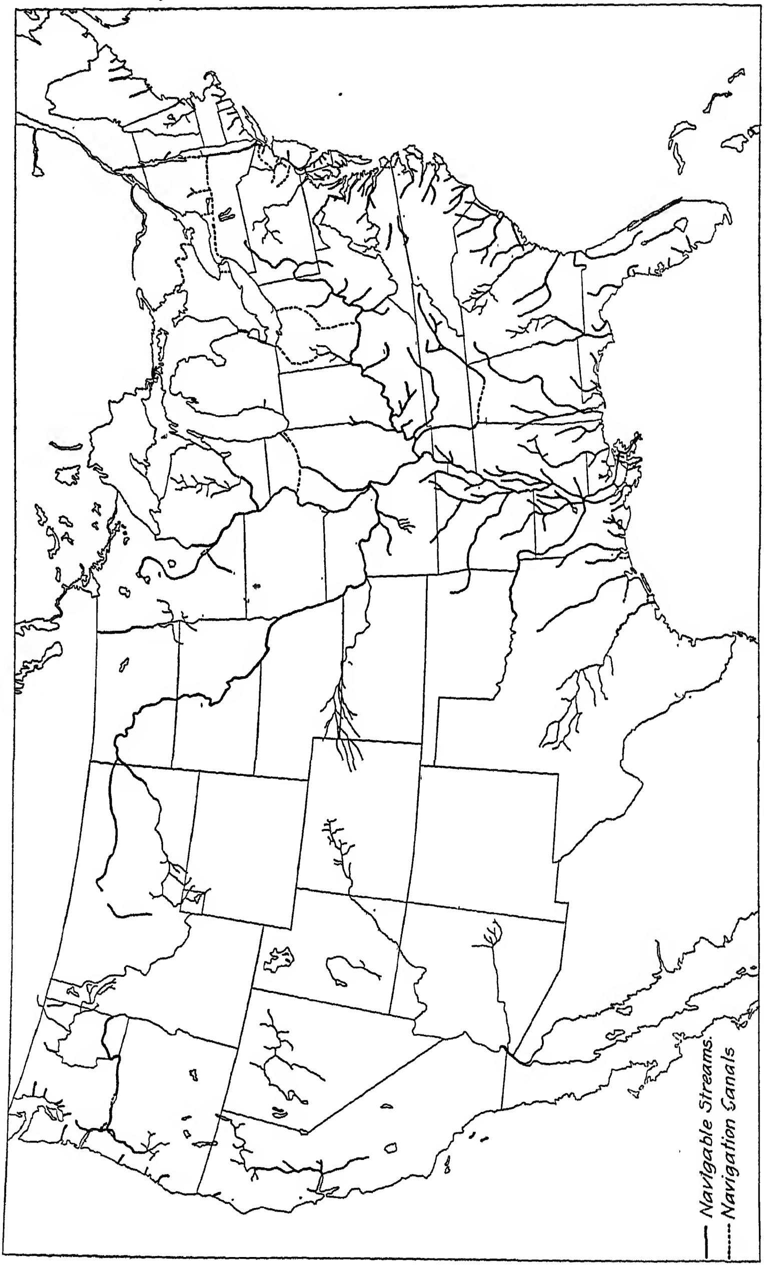

FIG. 351.—The Navigable Waters of the United States.

ordinate place. In the United States their practical importance has in many cases departed.

In Fig. 351 are shown the navigable waters of the United States. There are about 25,000 miles of rivers in the United States that are now navigable for boats of various drafts and perhaps a further equal mileage which can be made navigable. The Great Lakes are about 1,400 miles in length but furnish a much greater length of navigable waters. There are also about 2,100 miles of canals in the United States part of which are however not navigable in part at the present time.

The American canal at the Sault St. Marie carries more traffic than any other waterway of equal length in the world. This is because it controls the line of transportation from the iron mines of Minnesota, Wisconsin and Michigan to the furnaces along Lakes Erie and Michigan and of Ohio, Pennsylvania and Illinois. The great traffic over this short canal is unusual, as noted, and cannot fairly be used as an argument in favor of improving waters along lines on which no natural demand for navigation transportation exists.

With further development and a growing demand for cheap transportation of bulky commodities, it is not inconceivable that the importance of internal waterways may increase in the future, but that they will, in the United States, ever again even approximate the importance of railways is hardly conceivable. What the future may develop with growth in population and increase in the cost and value of fuel and in labor difficulties can only be surmised.

In late years there has been an attempt to arouse public interest and to create a public sentiment favorable to an immediate development of interior waterways. The more general development and utilization of internal waterways in Europe has been used as an argument in favor of the general development of waterways in this country. It is important to note, however, that there are already available in the United States more miles of navigable waters than in England, France, Belgium and Germany combined (see Table 65) and that the desirability of development of these resources in this country is purely a question to be determined from our own conditions. In the investigation of such problems their economic bearing should be determined as with all other problems, and no scheme for development should be advocated or adopted unless it can clearly be shown that its importance to the country will warrant the expense involved in construction, operation and maintenance.

TABLE 65.

Relative Length in Miles of Waterways and Railways in Various Countries of Europe and in the United States in 1905.

	Rivers	Canalized River	Canals	Total Waterways	Total Railroads
England and Wales	812	1,312	1,927	4,053	
France	796	970	1,777	7,485	2,445
Belgium	75	307	334	1,016	2,873
Germany	1,948	425	895	6,200	33,730
United States	26,400	1,410*	2,190	30,010	222,571

271. Outline of Factors of Navigation—Rivers, Canals and Harbors.—

I. General.

1. Necessity, desirability, feasibility, benefits, tonnage carried or estimated, competition.

II. Physical.

2. Location: A topography, B geology, C climate, D rainfall variations and extremes, E temperature (ice, anvigation season), F storms, G earthquakes.

III. Water Supply.

3. Streamflow: (gagings, records, storage, equalization of flow, variation of flow).

IV. Water and Navigation Laws.

4. Riparian rights: A rights of way, B condemnation, C litigation, D benefits and damages.

V. Development.

5. Surveys, hydrographic: A gagings, B soundings.
6. Surveys, topographic and land: A rights of way, B sites, C canal and channel locations, D flowage.
7. Dams: A foundations, B storage, C regulation, D wing dams.
8. Harbors, wharfs, jetties, piers, lights, channel marks, warehouses.
9. Locks: A size of vessels, B lift capacity, C gates, D time of operating, E lock operating machinery.
10. Equipment: A towing equipment, B lighting, C power (transmission, cost), D loading and unloading machinery.
11. Channels: A excavating, B dredging, C class of machinery.

VI. Labor and Material.

12. Method: A contract, B force account.
13. Labor: A nationality, B availability.
14. Material: A sources, B availability, C transportation, D distance, E cost.
15. Construction plant and equipment: A nature, B cost.

VII. Cost Estimates.

16. Promotion, administration, engineering, legal, time of construction, interest during construction, construction and overhead costs, financing, appropriations, bonds, discounts, interest, sinking fund,

*Great Lakes.

damages, benefits, tolls, maintenance, depreciation, operation, taxes, contingencies.

VIII. Financing.

17. Appropriation, stocks, bonds, securities, market values.

IX. General Conclusions.

18. Comparisons, discussion, financial returns, recommendations.

272. The Sewerage of Cities.—Of projects for the control of water those for the drainage and sewerage of cities are perhaps the most common and of the most general importance.

The overflow of storm waters, even for brief periods, may be highly objectionable in a village and not at all permissable in cities or large communities, while such occurrence in the country though undesirable may not be of sufficient importance to warrant an expensive remedy. In the country, or even in the village community, the vault or cess pool while objectionable may temporarily serve the purpose of disposal of household waste. In cities, with public water supplies, the waste waters are increased in quantities and if cess pools are used they would soon saturate the soil with filth and create unhealthful conditions. Sewers therefore become essential for the conveyance of such wastes to points where they may be discharged without serious consequences or where they may be treated and their injurious characteristics removed before they are discharged into surface waters.

273. Outline of Factors of Sewerage Projects.—

I. Purpose.

1. Uses and necessities of system, sanitation and removal by water carriage of domestic and industrial waste and storm water.

II. Source and Amount of Sewage.

2. Domestic: A quantity, B population present and prospective, C amount of water supply, D probable infiltration from ground water.
3. Industrial wastes: A quantity, B character of industry (dye works, tanneries, etc.).
4. Storm water: A quantity, B rainfall, C drainage area, D character, E records and gagings, F comparisons with similar places, G run-off formulas.

III. System.

5. Gravity flow, pumping (source of power, cost).
6. Sewers: A conduits (concrete, masonry, clay, metal), B capacity, C grade, D outfalls, E intercepting, F overflow.
7. Accessories: A manholes, B catch basins, C lamp holes, D vents, E traps, F pumps and ejectors, G plumbing.
8. Plant, A treatment (clarification, purification), B pumping.

IV. Disposal.

9. Dilution in stream: A stream flow (records and gaging).

10. Broad irrigation.
11. Settling and screening.
12. Treatment: A septic, B filtration (sprinkling and contact filters) (activated sludge, D chemical reduction (trade waste), E sterilization.
13. Sludge: A incineration, B fertilizer.

V. Ownership and Management.

14. Usually municipal ownership.

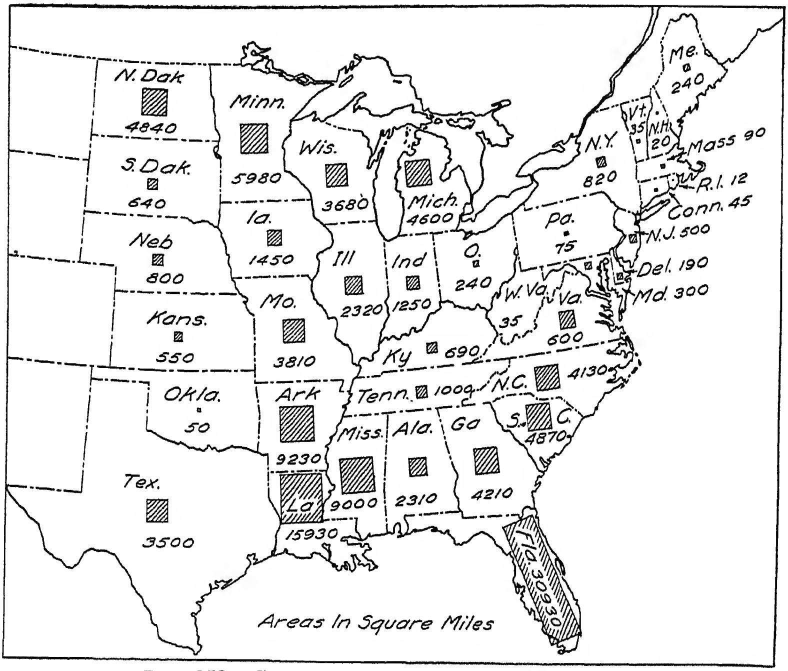

FIG. 352.—Swamp Lands of the United States.

VI. Cost Estimates.

15. Promotion, administration, engineering, supervision, legal expenses, time of construction, interest during construction, cost of construction and overhead, cost of financing, bonds, discount, interest, sinking fund, damages, benefits, maintenance, depreciation, operation, contingencies.

VII. Financial.

16. Tax roll, special assessment, assessed valuation, bond limit, interest, maintenance, depreciation.

VIII. General Conclusions.

17. Comparisons, discussion, recommendations.

274. **Drainage.**—For successful agriculture too much water is quite as detrimental as too little. There are many lands throughout the world that are too wet, periodically overflowed or permanent swamp

which cannot be used for agricultural purposes to advantage if at all under the present conditions. The description of swamp and wet lands in the United States is given in Table 66, and the swamp areas in the United States east of the Rocky Mountains are shown graphically in Fig. 352.

TABLE 66.

Swamp and Wet Lands of the United States.

STATE	Permanent Swamp Acres	Wet Grazing Land Acres	Periodically Overflowed Acres	Periodically Swamp Acres	Total Acres
Alabama	900,000	59,200	520,000	....	1,479,200
Arkansas	5,200,000	50,000	531,000	131,300	5,912,300
Cailfornia	1,000,000	1,000,000	1,420,000	....	3,420,000
Connecticut	....	10,000	20,000	....	30,000
Delaware	50,000	50,000	27,000	200	127,200
Florida	18,000,000	....	1,000,000	800,000	19,800,000
Georgia	1,000,000	....	1,000,000	700,000	2,700,000
Illinois	25,000	500,000	400,000	....	925,000
Indiana	15,000	100,000	500,000	10,000	625,000
Iowa	300,000	200,000	350,000	80,500	930,500
Kansas	....	59,380	300,000	....	359,380
Kentucky	....	100,000	300,000	44,600	444,600
Louisiana	9,000,000	1,196,605	....	....	10,196,605
Maryland	100,000	....	92,000	....	192,000
Maine	156,520	....	....	....	156,520
Massachusetts	20,000	....	39,500	....	59,500
Michigan	2,000,000	947,439	....	....	2,947,439
Minnesota	3,048,000	2,000,000	....	784,308	5,832,308
Mississippi	3,000,000	....	2,760,200	....	5,760,200
Missouri	1,000,000	....	1,439,700	....	2,439,700
Nebraska	....	100,000	412,100	....	512,100
New Hampshire	5,000	....	7,700	....	12,700
New Jersey	326,400	....	....	....	326,400
New York	100,000	100,000	329,100	....	529,100
North Carolina	1,000,000	500,000	500,000	748,160	2,748,160
North Dakota	50,000	50,000	50,000	50,000	200,000
Ohio	....	....	100,000	55,047	155,047
Oklahoma	....	....	31,500	....	31,500
Oregon	254,000	....	....	....	254,000
Pennsylvania	....	....	50,000	....	50,000
Rhode Island	....	....	6,000	2,064	8,064
South Carolina	1,500,000	....	622,120	1,000,000	3,122,120
South Dakota	100,000	....	511,480	....	611,480
Tennessee	639,600	....	....	....	639,600
Texas	1,240,000	1,000,000	....	....	2,240,000
Vermont	15,000	....	8,000	....	23,000
Virginia	600,000	....	200,000	....	800,000
Washington	20,500	....	....	....	20,500
West Virginia	....	....	23,900	....	23,900
Wisconsin	2,000,000	....	....	360,000	2,360,000
Total	52,665,020	6,826,019	14,747,805	4,766,179	79,005,023

Drainage engineering varies in character from the simplest construction of a tile drain or open ditch from a single farm to the most exten

sive projects involving perhaps, as in the case of the Florida Everglades, the drainage of thousands of acres by the construction of large canals. Such projects sometimes entail the diversion of head waters from the land to be drained and the construction of dams and levees to prevent the inroad of the sea or the overflow of rivers which adjoin the lands to be reclaimed, protected or improved.

The irrigation of extensive areas of land commonly involve the necessity of the drainage of the lower lands which are injured by seepage from the ditches and higher irrigated areas. This is commonly the result of over-irrigation and can be modified and minimized but not wholly prevented by the intelligent use of irrigation water. The extent of the injury to the lands of the U. S. Reclamatation Service (in 1916) from this cause is shown in Table 67.

TABLE 67.

United States Reclamation Projects Estimates of Seepage and Summary of Drainage Work to June 30, 1917.

PROJECTS.	DRAINS		Estimated Area Damaged by seepage acres.	Estimated Area Protected by Constructed Drains acres	Estimated Area to be Protected when all Drains authorized are constructed acres.
	Open miles	Closed miles			
Arizona: Salt River	....	....	6,400	....	....
Arizona-California: Yuma	14.5	4.0	8,000	12,000	52,000
Colorado:					
Grand Valley	.7	....	250	50	....
Uncompahgre	....	....	16,000	....	....
Idaho:					
Boise—					
Pioneer Irrig. Dst.	78.5	.8	10,500	30,000	30,000
Nampa-Meridian Dst.	43.7	....	6,200	50,000	50,000
Other parts of project	9.7	....	2,050	3,500	3,500
Minodoka	100.0	....	543	30,000	30,000
Montana:					
Flathead (Indian)	.18	2.97	360	1,240	1,240
Huntley	15.77	43.29	1,704	20,000	24,000
Sun River	....	....	2,250	....	......
Montana-North Dakota:					
Lower Yellowstone	4.5	1.1	1,300	1,600	1,600
Nebraska-Wyoming:					
North Platte	20.4	14.0	3,000	5,000	6,000
Nevada: Truckee-Carson	9.5	3.99	11,000	11,000	16,000
New Mexico: Carlsbad	9.0	3.9	3,061	2,769	5,000
New Mexico-Texas: Rio Grande.	11.5	....	55,000	5,100	......
Oregon:					
Klamath	67.7	5.7	6,200	17,000	29,600
Umatilla	10.0	......	200	2,000	2,000
South Dakota: Belle Fourche...	....	....	3,250	....	......
Wyoming: Shoshone	11.57	67.90	5,000	14,000	17,500

275. Outline of Factors of Land Drainage Projects.—

I. Physical.

1. Location: A topography, B geology, C hydrological conditions, D climate, E rainfall and variations, F temperature, G transportation (roads, railroads), H markets.

II. Land.

2. Area of District, area to be drained, soil and subsoil, fertility, necessity for fertilizer, cultivation, vegetation, timber.
3. Drainage: A necessity, B feasibility, C increase in productivity, D improvement in health conditions, E value.
4. Ownership, legal rights.
5. Drainage laws: A drainage district organization, B assessments (damages and benefits).

III. Hydrology.

6. Source of water (from district to be drained, from country draining into district, from flood overflow, from tide overflow).
7. Surface water: A flow of streams (records, etc.), B drainage area (swamp, bayous), C storage, D rainfall, E diversion of streams, F topography.
8. Ground water: A disposal, B works needed (open ditches, underdrains, levees, floodways, outlets, pumping plant).

IV. Development Works.

9. Surveys: A methods, B lines run, C natural drainage channels, D ditch locations, E rights of way, F profiles, G maps, H outlets. mensions and foundation.
10. Intercepting and diverting levees and channels: A capacity, B dimensions and foundation, C soil.
11. Storage and flow retarding basins and channels.
12. Levees: A stripping, B stratification and nature of subsoil, C muck ditches, D borrow pits.
13. Channels and floodways: A size, B berms, C slopes, D construction, E protection (paving, mats).
14. Ditches and drains: A capacities, B spacing, C depth, D length, E grade and protections, F character of soil.
15. Bridges, roadways, culverts, weirs and drops.
16. Pumping equipment: A location and capacity, B character of fuel, C cost.
17. Outlets: A permanency, B protection, C gates (tide gates, etc.) D foundations, E consideration of effect on adjacent or contiguous areas.

V. Construction.

18. Under contract or force account.
19. Labor: A nationality, B teams, C availability, D cost.
20. Material: A sources, B distance, C transportation, D cost delivered.
21. Machinery: A dredges (floating and caterpillar type dipper, clam shell, suction, dragline), B scraper (wheel, drag).

VI. Cost Estimates.

22. Cost of Promotion, administration, engineering, supervision, legal expenses, time required for construction, interest during construction, cost of construction and overhead, cost of financing, bonds, discount, sinking fund, payments, interest, assessment of benefits and damages, cost of maintenance, depreciation, operation, contingencies, taxes, estimated returns and profits.

VII. General Conclusions.

23. Comparative data from similar developments, adequacy of works, conclusions, recommendations.

276. Flood Protection.—Flood protection works are frequently a part of the works for the drainage of cities and agricultural lands. With the growth of settlements, of homes, farms and manufacturing establishments on the flood plains of rivers, the event of even occasional overflows becomes too serious to be permitted to continue. As a consequence some of the most important engineering undertakings are included under this subject and demand not only a most profound study of the hydrology of floods but also the design and construction of the most economical works for their control.

277. Outline of Factors for Flood Protection Investigation.—

I. Physical Conditions.

1. Location: A topography, B geology, C area to be protected, D drainage area producing floods, E climate, F rainfall, G temperature, H hydrological conditions, I relation of area to flood plains and flood heights.

II. Land and Property.

2. Character: urban, residential, industrial, rural, agricultural.
3. Land: amount, character, productiveness, value.
4. Effect of floods: A protection (necessity, desirability, feasibility), B value of lines and property involved.

III. Floods.

5. Flow of streams: A gagings (magnitude and frequency of flood heights, records), B drainage area (characteristics, topography), C rainfall.
6. Channel storage, stream congestion.

IV. Laws.

7. District organization: A legality, B rights, C damages and benefits, D litigation.

V. Development.

8. Surveys: A topography, B channel and levee locations, C rights of way, D change in railroads, roads, pole lines, etc.
9. Works needed: A confining, B controlling, C intercepting, D diverting, E impounding and flow retarding works, F capacities.
10. Dams (foundations, outlets, spillways).
11. Levees and channels: A height, depth, capacity, grades, B erosion, C revetments and protection, D currents and waves.

12. River training: A revetments, B pavements, C jetties, D wing dams.
13. Bridges (roadways, railways).

VI. Construction Methods.

14. Contracts, force account.
17. Labor: A nationality, B availability, C teams, D cost.
18. Camp requirements.
19. Material: A sources, B distance, C transportation, D cost.
20. Machinery, type and class available for economic construction.

VII. Cost Estimates.

21. Cost of promotion, administration, engineering supervision, legal expenses, time of construction, interest during construction, construction camp, original cost and maintenance, construction costs, financing, bonds, discounts, interest, assessment, benefits and damages, maintenance, depreciation, operation contingencies.

VIII. General Conclusions.

22. Comparative data, adequacy of works, discussion, recommendations.

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